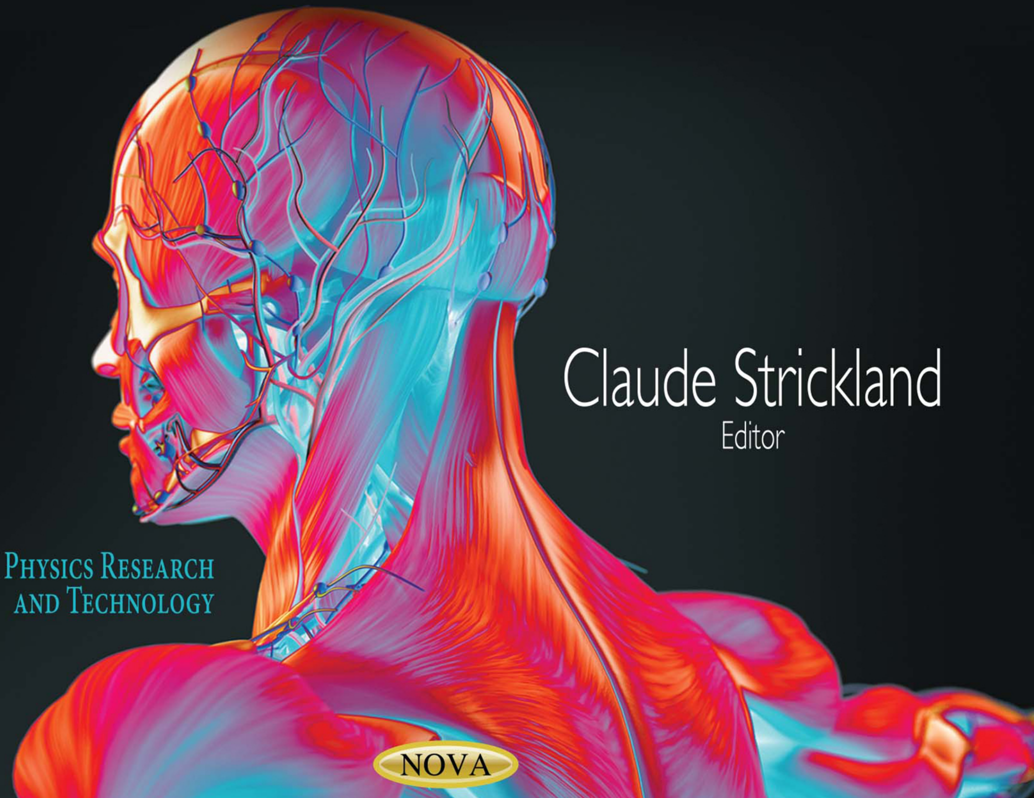
Thermal Imaging

Types, Advancements and Applications



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Chapter 1

THERMAL IMAGING CAMERAS IN THE DETECTION OF HUMAN CADAVERIC REMAINS

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ABSTRACT

Detection of cadaveric remains using Thermal Imaging (TI) is a relatively new concept. Recent studies support the usefulness of continued use of TI in later stages of Missing Person's searches, when the hope for recovering the person alive has diminished, and the search has been deemed a recovery.

Searching for missing persons usually involves difficult terrain often times of densely forested environments that are not conducive to aerial searches. Ground searches involve lines of volunteers visually inspecting the area assigned as the group advances over a given location. TI is a standard piece of equipment often utilized during the initial phase. However, in the later stages during the search many of the resources may be retracted and hope of finding the body dwindles.

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Recent studies have proven the continued use of hand held TI cameras can increase the likelihood of a recovery even as late as the advanced decay stage by using heat signatures from colonizing insects on the cadaver. Time frames can be determined based on seasonality, weather, size and mass of the individual to maximize the search efforts without added cost of new equipment.

Future research into depth that TI can detect clandestine shallow burials would provide useful to law enforcement as it would enable the recovery of not only the victims but important evidence that would lead investigators to the perpetrators of the crimes.

1. INTRODUCTION

Thermal Imaging has been used in a wide variety of ways, only recently has its application to Forensic Anthropology been explored as a means of detection of missing persons cadaveric remains (DesMarais, 2014). Thermal imaging began as a means for combat personnel to detect heat signatures of individuals at night, later it was adapted by forestry and law enforcement to locate individuals in large areas from the air in low light (night) conditions (Maurer, Driggers, & Wilson, 2005) (Leonardo, 1961) (Killam, 2004) (Geddes, 2010) (France, et al., 1992) (De Loor, 1969) (Workman, 2001). Fire personnel adapted TI further, making handheld versions that are capable of functioning in adverse conditions, durable and compact enough for use in outdoor settings while continuing to image at great distances detecting objects with heat signature differences of fractions of a degree (Amon, Bryner, Lock, & Hamins, 2008).

Most fire departments have TI cameras and utilize them during search and rescue events when a person has been reported missing. The Fire fighters who are active members of Search and Rescue teams will use them during the initial search but suspend their use during the later stages when the mission changes from a rescue to a recovery; when the likelihood of finding the person alive has diminished.

Recently it’s been shown that the use of TI can continue into the later portion of the missing persons search; the recovery phase incorporating the postmortem interval, utilizing the heat signatures from decomposition and the extreme thermal signatures of insect larvae which is dependent on time, temperature, and cadaver mass (DesMarais, 2014).

Thermal imaging of cadaver detection works best in low light (night) conditions, during times when temperatures fall in the optimum temperature range for insect activity (50 to 95 °F) (Leonardo, 1961) (Block, Baust, Franks, Johnston, & Bale, 1990). If the search is during a timeframe that is not conducive to insect activity the recovery can potentially be continued when the temperature again reaches the optimum threshold (barring scavenging from predators during that paused timeframe), and decomposition would continue in a natural progression. The operator of the TI would view the heat signatures from decomposition and insect larval masses as increasingly bright amorphous forms of light that, as the larval masses increase in size, more closely register a heat signature that resembles the remains as a whole. When the masses are at their largest, during the active decay stage, they can be detected at a distance of over 114 feet (DesMarais, 2014).

Although detection of cadaveric remains in above ground settings brings closure to some families future directions in the use of TI would encompass both the forensic field by detection of clandestine graves bringing justice to the perpetrators with the likelihood they would be held accountable for the misdeeds they inflicted on their victims, and the archaeological potential for site identification which would expand our knowledge of past peoples.

2. THERMAL IMAGING

All objects over absolute zero temperature emit infrared energy; this type of energy is found beyond the visible light spectrum, having longer wavelengths than visible light. Typically thermal imaging cameras (TIC) view warmer objects, objects emitting more infrared energy (IR) as white while cooler objects would display as shades of gray or color (Woodworth, Thermal Imaging for the Fire Service, Part 3: Thermal Characteristics, 1996).

The first infrared sensitive cameras developed in 1929 were used by the British military for antiaircraft defense (Wimmer, 2011). Nearly 20 years later, an infrared line scanner (taking over an hour to produce a single image) was developed (Palmer Wahl Instrumentation Group, 2007). The US military saw the value in these detectors and classified the technology for sensitive military applications. It wasn't until 1966 that the first real-time imager was developed, paving the way a few short years later for the first thermal imager used by the Royal Navy for shipboard firefighting (Palmer Wahl Instrumentation Group, 2007) (Wimmer, 2011).

Prior to 1991 thermal imagers were cost prohibitive. Due in part to continued governmental contracts for development of TI technology, the practical application expanded to assisting the military personnel in combat situations at night by detecting heat signatures of combatants (Maurer, Driggers, & Wilson, 2005) (Wimmer, 2011). This drove production up and cost down. After the Gulf War the cost decrease led the way for thermal imaging into many different industries.

1994 saw the commercial application of thermal imaging with law enforcement, forestry personnel and border patrol by utilizing TI in searching large areas at night from the air for individuals on the ground (Leonardo, 1961) (Killam, 2004) (Geddes, 2010) (France, et al., 1992) (De Loor, 1969) (Workman, 2001).

Firefighting needs took the technology a step further making the hand held cameras lightweight and durable with the ability to function in adverse conditions. The readings can be viewed on a built in monitor (Figure 1) or as with some models the image is sent wirelessly to a monitor at the incident command. With the advent of Lithium Ion batteries the handheld TIC could be utilized for over four hours on a single charge (Palmer Wahl Instrumentation Group, 2007).

2.1. Missing Persons Searches

Many firefighters are members of Search and Rescue teams, realizing the potential TI would have in locating missing individuals they began utilizing them during search and rescue missions when a person has been reported missing.

The structural framework of Search and Rescue teams are much the same as Incident Command Systems (ICS) they are designed to expand or contract as the mission dictates (ASTM, 2014) (Department of Homeland Security, 2008) (Volunteers in Police Service Program, 2010). Each Search and Rescue team will typically consist of an emergency manager who works with elected officials ensuring unified objectives of the activities. They coordinate the components of the mission regarding availability and readiness of resources, correcting for shortfalls, and may call on mutual aid as the situation dictates. Department heads (fire, police, EMS, etc.) collaborate with the emergency manager ensuring that specific capabilities are integrated and that the members have met and maintain the proper training necessary (Riker, 2002). Emergency responders make up the recovery teams under the department heads. While all working toward a common goal, the members bring with them unique specializations that can be called on should they be needed; divers, canine handlers, tracking and communications experts among others.

Typically missing person searches are dictated by the conditions of the event itself. Age of the individual, weather, terrain and time of day these all play a part in directing the size, duration and equipment required (Department of Homeland Security, 2008). The emergency manager uses the event information to decide not only how few or many members are needed to adequately search but also decides when the mission should evolve from a rescue to a recovery. It is during this transition that the majority of the resources are recalled including thermal imagers.

In the search for a presumed deceased individual fewer volunteers are allocated, and those specializing in cadaver searches are retained or employed. Forensic anthropologists and cadaver dog teams head up the remainder of the search parties until the search itself is called off. Despite the advanced training of these professionals to locate postmortem and osseous remains, the search is still remarkably difficult as cadaveric remains in the later stages of decomposition blend with the surroundings as leaf litter and ground cover obscure the remains. While cadaver dogs are reported to be highly acute at finding remains they are limited by availability, the area to be covered, and terrain. The availability of these two specific resources is also sporadic and may require monetary compensation for their expertise. Coupling TI use with these trained professionals would increase the potential of locating the missing person exponentially.

3. DECOMPOSITION

Recently it has shown the potential of continued utilization of TI use into the later portion of the missing persons search, (i.e., the recovery phase) would increase the likelihood of locating the individual (DesMarais, 2014). In research using juvenile pig cadavers (*Sus scrofa domesticus)* weighing approximately 35-40 pounds was conducted. Despite their size the remains were successfully detected over 114 feet in low-light (night) conditions in a wooded environment during the advanced decay stage. The nonhuman model is has been widely accepted for human decomposition studies (Anderson & VanLaerhoven, 1996) (Grassberger & Frank, 2004) (Komar & Beattie, 1998) (MacAulay, Barr, & Strongman, 2009) (Schoenly & Hall, 2001), the weight range of the juvenile pig cadavers (48-77 pounds) was an appropriate size model for comparison with the size of the average adult human torso (Catts & Goff, 1992) (Sharanowski, Walker, & Anderson, 2008) (Anderson & VanLaerhoven, 1996) (Komar & Beattie, 1998).

After death cadavers go through 6 stages of decomposition; as described by Payne (Payne, 1965). The first fresh stage (beginning at the time of death), second bloat stage, third active decay stage (started when there was penetration of the skin by insect larvae), fourth advanced decay stage (started when most of the flesh had been removed from the carcass and the odors of decay began to fade), the fifth dry stage (started when there was only dry skin, cartilage, and bones remaining and insects were still present), and the sixth remains stage (beginning with the absence of all carrion-feeding insects).

During the fresh stage, cadavers undergo algor mortis, a reduction in core body temperature at a rate of approximately 1.5°F per hour beginning at the time of death continuing until ambient temperature is reached (Di Maio & Dana, 1998) (Clark, Worrell, & Pless, 1997) (Dix, Laposata, & Moseley, 1994). Accompanying processes of autolysis and putrefaction span the duration of decomposition from fresh to advanced stages. This overgrowth of bacteria found within the digestive tract can cause a minimal elevation in postmortem body temperature (~0.9°F) (Hutchins, 1985), scenarios that would themselves not be detected by TI. However, during this fresh stage in decomposition the insects attracted to cadaveric remains begin colonizing the bodies. The colonization causes an increase in the rate of putrefaction by creating openings in the skin. The openings allow exogenous aerobic bacteria to enter the body and by secreting proteolytic enzymes, which aid in tissue destruction (Zhou & Byard, 2011). The increase in the rate of putrefaction coupled with the increasing heat signatures from the larval masses produces a remarkable amount of heat during this timeframe.

While some studies associate the increase in heat from the cadavers to decomposition (Scott, 2016) (Pearson, 2014), the heat signatures from that alone are not great enough to differentiate the body from the surrounding environment effectively. While the insect masses do increase decomposition it is because of the thermal emissions from the larvae themselves that cause such a radical heat difference between the body and the surroundings for the TI to detect (DesMarais, 2014) (Heaton, Moffatt, & Simmons, 2014) (Pearson, 2014).

4. ENTOMOLOGY

Blowflies (Diptera: Calliphoridae) in particular are typically the first insect species to arrive at cadaveric remains (Byrd & Castner, 2010). Flies tend to feed on the cadaver and lay eggs typically in the eyes or body orifices; they will also lay eggs in areas of trauma (open wounds) because they are sources rich in nutrients.

At an ambient temperature of 70°F, fly larvae will hatch within 23 hours and go through 3 instars or stages of growth, consuming the carcass by scraping the flesh with paired mouth hooks (Castner, 2010). The first instar will typically last 27 hours, the second 22 hours and the third lasts approximately 130 hours. Once the third instar is complete the larvae will migrate away from the body and pupate for a final 143 hours before emerging as an adult fly (Cleveland Museum of Natural History, 2006).

As flies are the first to arrive at a cadaver, beetles (Coleoptera: Silphidae) of various genera are the last to leave, as they are primarily predacious and feed on fly larvae (Byrd & Castner, 2010) (Castner, 2010) (Forbes & Dadour, 2010).

While TI would not necessarily pick up on the body temperature changes itself after death, it does register the colonization of insect larvae associated with it, and thus can detect throughout the timeframe of this colonization. Fly larvae masses are known to thermoregulate. Small larval colonies (1200 members) can maintain temperatures between 36.5° -57.2°F above ambient (Heaton, Moffatt, & Simmons, 2014) (Pearson, 2014). Larger larval masses (2500 or more) have been known to reach temperatures of 122°F, the limit at which thermal death occurs (Heaton, Moffatt, & Simmons, 2014) (Pearson, 2014) (Block, Baust, Franks, Johnston, & Bale, 1990).

As mentioned previously, a recent study successfully demonstrated the ability of TI to detect cadaveric remains by heat signatures of insect colonization at 114 feet (DesMarais, 2014). In a forested cold climate region in mid-autumn seven juvenile pig carcasses were placed out for study. One of the pig cadavers was selected as a control to test the TI cameras ability to detect heat signatures from decomposition alone, while the remaining six were allowed to be colonized. What was determined was as long as insect larval masses were active and present the heat generated by them was significantly well above ambient temperatures of the surrounding environment. Because of the lack of insect colonization and the colder ambient temperatures, the control expressed very little difference visually from the start to the end of the experiment; in fact after day one TI visualization was nearly indistinguishable from the surroundings for the length of the study. Despite the occasional frost and dip of temperatures below optimum temperature range for insect activity (50-95°F) it became apparent that as the ambient temperatures rose into the optimum range the larval temperatures too would rise. As they resumed active behavior they again began producing temperatures well above ambient. This cycle continued as long as there was abundant food to support the increased activity, despite decompositional stage.

Injuries, size, and health of the individual will dictate the timeframes of not only the duration of the search and rescue, but the length of time and intensity of the colonization and detection by TI. Injuries will allow immediate access for larval masses creating faster colonization, where as it may take two to four days for the larvae to penetrate the flesh, injuries (open wounds) eliminate this delay.

Size and health of the body will dictate the length of time for the larval masses to transition the cadaver to the final stages of decomposition. If the individual is small framed the larval colony would be smaller and would exhibit a thermal emission that is smaller in size than that of someone whose frame would accommodate a larger colony. Very small persons would also exhibit a faster decompositional transition thus reducing the timeframe for a TI search.

Based on the temperature and visual data collected an optimal time frame can be derived during which TI use would be most successful and subsequent searches could be planned for (Table 1).

5. USE OF THERMAL IMAGING

5.1. Time of Day

In general TI detected the greatest thermal emissions (21°F above ambient temperatures) during the advanced decay stage which lasted the longest when larval masses were at their most active, during this stage the cadavers were imaged the clearest from the greatest distances (DesMarais, 2014).

It has been postulated that searches by unmanned aerial vehicles (UAV) during early morning hours would provide the greatest temperature difference between early decompositional heat signatures seen in the abdomen (the site of greatest putrefaction occurs) versus those of the environment (Scott, 2016). However, current studies identified the heat signatures as that of larval masses not decomposition alone (DesMarais, 2014) (Pearson, 2014) (Heaton, Moffatt, & Simmons, 2014). Also as there is a significant cooling of temperatures over the evening hours, larval masses converge to inner cavities to maintain optimum temperatures; as seen in cooler climates when evening temperatures fall below temperatures that are conducive to larval survival. Thus early morning TI use would not be recommended in colder climates during cooler months.

Mid-morning to early afternoon TI use would be less than ideal but would extend search time parameters and allow for safer traversing conditions.

Imaging during the day can bring challenges as objects in the environment absorb radiant energy throughout the day (Woodworth, Thermal Imaging for the Fire Service, Part 4: Thermal Imaging Devices, 1997), causing a background modeling that can confuse heat signatures of these objects with heat signatures of the insect larval masses.

Staff with more experience using TI and ambient signatures during this time frame would have less difficulty (Riker, 2002). Searchers new to TI would be recommended to avoid timeframes of greatest midday temperatures for a few hours afterward.

The ideal timeframe for TI search would be a few hours after the greatest midday temperatures (late afternoon/ early evening) into the early evening taking into consideration safety of traversing irregular ground in low-light conditions. During this timeframe the contrast between larval thermal emissions would be radically higher than the surroundings. However heavily shaded locations exhibit less radiant energy signatures allowing for greater larval temperature differentiation and can extend the search timeframe to include much of the day as well as early evening hours.

5.2. Seasons

While time of day dictates the optimum ability of TI to differentiate larval mass heat signatures from the surroundings, larval activity is dictated by seasonal temperatures. Temperatures that are too high (>104°F) or are too low (<28°F) are not conducive to insect or larval activity (Block, Baust, Franks, Johnston, & Bale, 1990). Despite having the ability to produce their own heat, when temperatures are too low larvae will migrate into the body cavities and at times produce a froth-like substance to insulate them from the cold (DesMarais, 2014). In temperatures below 50°F numbers of surviving larvae decrease and the remaining larvae fall into a stuporous stage (Block, Baust, Franks, Johnston, & Bale, 1990). The decrease in numbers and activity of the larvae results in a lower heat potential for TI cameras to image. However when ambient temperatures rise into the optimum range the larval activity increases restarting the cycle of decomposition, this provides increased thermal emissions for the TI to detect (DesMarais, 2014). While this study deals with TI imaging in cold climate environments it is known that insect larvae will fall into a stuporous stage if temperatures are too high, only actively feeding when temperatures fall.

5.3. What to Expect from Imaging

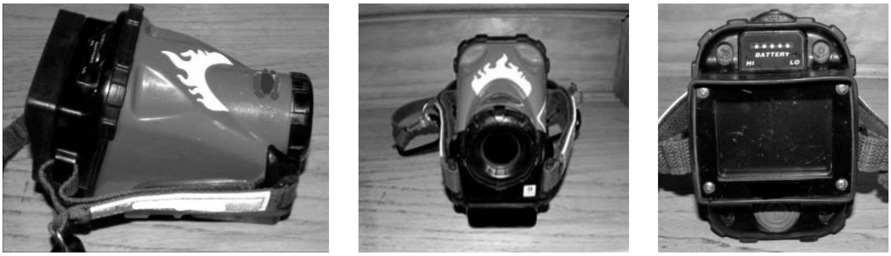
The searcher will be expected to understand the constant fluctuation between radiant energy, larval mass thermal emissions and decompositional changes and what it will mean when viewing the surroundings. Standard imagers used by fire departments are calibrated to detect ranges of high thermal emissions, temperatures less than 200°F are viewed in black and white; the lighter the object appears the higher the temperature. Despite the gray scale imaging this equipment is able to detect temperature differences to one-tenth of a degree from distances greater than 600 feet. During the first stages of the recovery a TI will image a body similarly to when it was still alive. As cooling progresses the trunk of the body will cool slower then dependent areas such as arms and legs, due to increased bacterial activity in the digestive tract. Once insect colonization has begun, bright amorphic areas of light will be apparent wherever the larval masses are forming. These areas will grow larger and brighter as the colony increases in size and activity. TI definition would significantly increase throughout active decomposition. Beginning between two to four days into the active decomposition the thermal image will gradually take on basic attributes of the body. The larval mass will always image much brighter than the surrounding environment (Figures 2a and 2b) until the food source for the larvae has been exhausted then the emissions will decrease in intensity and size until eventually the cadaver reaches the dry stage and lastly the remains stage when all insects have left the body.

5.4. Drawbacks of TI Imaging

While it is a novel idea to employ smaller imagers that have the capability to image in color at lower temperatures it is not recommended. So long as the more expensive durable fire department devices were already available they should be utilized. Where inclement weather and drops play a major factor, these cheaper imagers would not be durable enough for prolonged use in rugged environments.

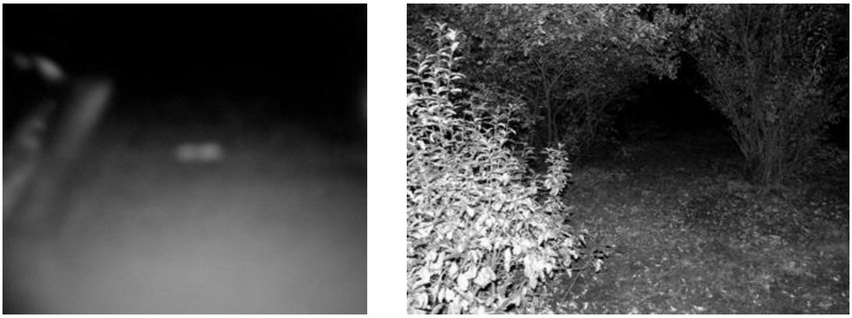
TI is ideal for the rough terrain of search and rescue events however; it is not ideal if the person is believed to be in a body of water as imagers are incapable of penetrating the reflective surface.

Aerial imagers in large open areas would save time as they have the capability to search larger areas faster. But, in areas that are heavily wooded or that have thick brush these devices may not be able to penetrate the area sufficiently to be able to differentiate the amorphic bright signature of the larval masses from objects emitting radiant heat, or small forest creatures. As this option is likely not cost effective unless already deployed for the initial search and rescue it would most likely not yield better results than a ground search in mountainous/rugged terrain.



(a) (b) (c)

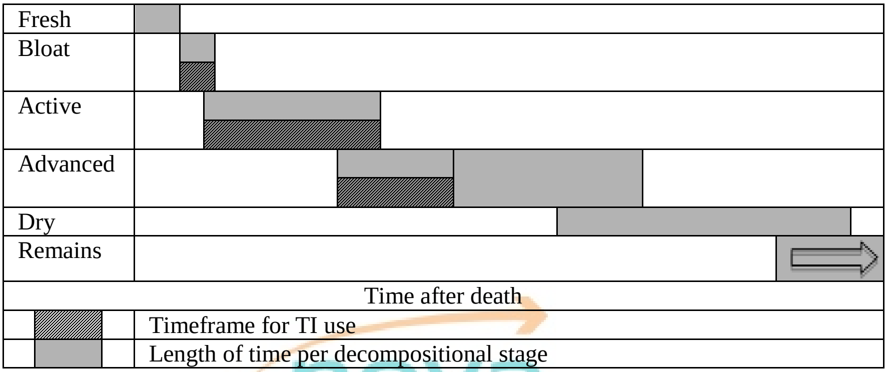
Figure 1. Typical Fire Department TI Camera: (a) side view; (b) lens/ front view (c) display screen/ back view.



(a) (b)

Figure 2. Larval mass in pig carcass at 30 feet: (a) imaged through a TI Camera; (b) imaged through a digital camera with flash.

Table 1. Timeframe for stages of decomposition and ideal time for TI use



6. DISCUSSION

The primary goal of all missing persons searches is to recover the individual. When the expectation of survivability has been exhausted and the majority of resources have been recalled continued use of thermal imaging by trained personnel coupled with any ancillary cadaver search experts will increase the success of the recovery mission.

After death it takes several hours for the cadaver to cool to ambient temperatures. However insects attracted to cadavers begin colonization hours after death by laying egg masses in moist areas of the body. On the second to fourth day the larval have hatched and the thermal emission from the masses, seen as at first as small amorphic areas of white continue to enlarge in both size and thermal intensity. The thermal signature from the larvae continue along with the process of decomposition until the body can no longer provide a sources of nutrients to the larval masses, usually ending when the cadaver reaches the remains stage.

Use of TI during the active decay and into advanced decay stages would provide the greatest and largest contrast between larval masses and the ambient temperature. Other key factors to take into consideration are time of day and season. Avoidance of mid-day when radiant energy is at its peak; searching in cooler lowlight settings is ideal as there would be less radiant distortion from the surroundings, this is most important during the summer months but can occur in autumn and spring as well when warmer temperature fluctuations occur. When seasonal temperatures dip below the optimum range as seen in spring and fall the processes of not only decomposition slow but insect activity slows as well, however both resume when temperatures return to optimum. For this reason TI use in the winter months, when temperatures remain below optimum, is not recommended. Barring scavenging from animal activity, decomposition and insect activity resume with the seasonal temperature increases and therefor TI use can be utilized with success.

7. FUTURE DIRECTIONS

7.1. Clandestine Graves

More research needs to be invested in detection of cadavers in clandestine settings; shallow burials and materials of opportunity that are designed to hide bodies from visual observation. Research of this type would expand TI use from search and rescue/recovery missions to all types of missing person searches, including victims who are feared to have been murdered, and the body hidden.

Recovering victims of crime would not only bring a type of closure to the families but it creates an opportunity for law enforcement to collect and recover evidence in order to secure a conviction of the perpetrators.

7.2. Archaeological Potential for Site Identification

Other promising research is the investigation into the archaeological potential for site identification a novel approach for TI use that needs more attention. Hyperspectral imaging processes light across the electromagnetic spectrum including the infrared range TI detects. A recent study by scientists from McGill University proved the potential of hyperspectral imaging, this measures changes in light coming from soil and plants (Bland, 2010). Their research was reported to identify animal graves some up to 8-feet deep and greater than 40 years old.

This would not only help identify sites that are thousands of years old but also have the potential to help law enforcement solve missing persons cases.

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BIOGRAPHICAL SKETCH

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Research and Professional Experience:

Professional Experience

- *Forensic Anthropological Consultant/Executive Assistant,* Forensic Pathology and Legal Medicine, Providence, Rhode Island. Consulting for Federal, State, and Local agencies, I assist in the assessment of time since death and time since injury, tool mark comparison, and trauma analysis on both bone and soft tissue. Assisting with primary and secondary autopsies as needed.
- *Consulting Forensic Anthropologist,* Lead Me Home, a not-for-profit organization dealing with missing persons, New York/Pennsylvania Division. I provide a determination of Medicolegal significance of skeletal material recovered from areas where individuals have been reported missing.
- *Forensic Anthropologist/Archaeologist II,* Mashantucket Pequot Tribal Museum under a Cultural Resource Management (CRM) operation for the American Battlefield Protection Program (ABPP) of the National Parks Service, Mashantucket, Connecticut. One aspect of my employment is the analysis of osteological material for the museum. The other aspect requires the application of Archaeological techniques in field survey and excavation phases I, II, and III. The project is a collaboration between tribal members, archaeologists and military historians.
- *Laboratory Technician,* Boston University Anatomy and Neurobiology Department, Boston, Massachusetts.
- *Epidemiology Research Assistant* for the Rhode Island's Child Death Review Team. Brown University, Providence, Rhode Island.
- *Anthropological Intern* for the Rhode Island Medical Examiner's Office, Providence, Rhode Island.

Field Experience

- *Examination* of skeletal material in a suspected homicide of Forensic significance. Anthropological techniques were employed in the examination and identification of traumatic injury of a severely decomposed individual recovered from a boat hull.
- *Excavation and Analysis* of archaeological skeletal remains with a multi-national team in Abu Erteila, Sudan.
- *Recovery* of skeletal remains evidence in a suspicious death of Forensic significance. Anthropological and archaeological techniques were employed in the identification and recovery of a skeletonized individual in a makeshift clandestine grave at the bottom of an elevator shaft.
- *Field School in Archaeology,* Battlefield Archaeology through the University of Connecticut excavating New England battlefield sites involved in The King Phillip’s War. The project is a collaboration between tribal members, archaeologists and military historians.
- *Recovery* of remains and evidence from a “cold case.” Anthropological techniques were employed (sifting) to locate remains and evidence believed to be in over 200lb of dirt stored at the Massachusetts OCME.
- *Search and Recovery* of remains from a 20 year-old “cold case” in Woburn, Massachusetts. Applied forensic anthropological techniques (subsurface testing) to locate remains believed to be in a clandestine grave.
- *Search and Recovery* of remains from a 20 year-old “cold case” in Woburn, Massachusetts. Applied forensic anthropological techniques (subsurface testing) to locate remains believed to be in a clandestine grave.
- *Field School in Archaeology*, The Rhode Island State Home and School Project, involving the excavation of a series of Orphanage buildings from 1900’s located on Rhode Island College Property..

Professional Appointments:

Lecture by Invitation

- *Brief Overview of Non-Human Skeletal Assessment*, Mashantucket Pequot Tribal Museum, Ledyard, CT.
- *Detection of Cadaveric Remains by Thermal Imaging Cameras*, Boston University Forensic Sciences Society (BUFSS) at Boston University School of Medicine, Boston, Massachusetts. The lecture discussed cadaver detection timeframes in New England using thermal imaging technology based on insect radiant energy, seasonality, and cadaver size.
- *Forensic Entomology for the Medico-legal Death Investigator*, Medico-legal Death Investigation course taught at Boston University School of Medicine, Boston, Massachusetts. The lecture covered an introduction to the field of entomology, insect biology; identification and collection of terrestrial and aquatic species commonly associated with forensic settings as well as a basic understanding of time since death, and accumulated degree hour/day calculations.

Teaching Experience

- *Postgraduate Teaching Assistant*, Forensic Pathology and Medicolegal Death Investigation course taught at Boston University School of Medicine.
- *Postgraduate Teaching Assistant*, Forensic Pathology course taught at Boston University School of Medicine.
- *Postgraduate Teaching Assistant*, Medicolegal Death Investigation course taught at Boston University School of Medicine.
- *Teaching Assistant*, Blood Spatter Pattern Analysis short course taught at Boston University School of Medicine.
- *Teaching Assistant*, Forensic Anthropology course taught at Boston University School of Medicine.

- *Teaching Assistant,* Citizens CSI Academy, Holliston, Massachusetts. 10-week course presented by Boston University School of Medicine, through the Department of Anatomy and Neurobiology in Applied Forensic Sciences and Criminal Investigation. Covering the following topics: DNA, Forensic Pathology, Forensic Anthropology, Trace Evidence, Blood Stain Pattern Analysis, Toxicology, Pattern Evidence, Ballistics, Mass Disaster and Crisis Management.

Memberships:

- American Standards Board –Board Member: Patterned Injury; Forensic Anthropology
- International Association for Identification –Affiliate Member; Board Member of the Forensic Anthropology Subcommittee
- American Academy of Forensic Sciences – Affiliate Member
- American Association of Physical Anthropologists –Member
- American Anthropological Association -Member

Honors:

- Certificate of Appreciation Award from the Middlesex District Attorney –Gerard T. Leone, Jr. Boston, MA. For my contribution to a cold case.
- Certificate of Appreciation Award from the Middlesex District Attorney –Gerard T. Leone, Jr. Boston, MA. For my contribution to a cold case.
- Sam Houston Award in Anthropological Achievement through Rhode Island College
- Graduated Cum Laude from Rhode Island College

Publications from the Last Three Years:

- *Article:* Angel M. DesMarais, M.S. “Detection of Cadaveric Remains by Thermal Imaging Cameras.” The Journal of Forensic Identification # JFI-2014-5-489.
- *Book Review:* Manhein, M.H. Bone Remains Cold Cases in Forensic Anthropology. 2013. LSU. Reviewed for the Journal of Forensic Identification #JFI-2014-2-203.

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Chapter 2

PASSIVE AND ACTIVE THERMOGRAPHY FOR THE DETECTION OF SUBSURFACE MALIGNANT LESIONS

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ABSTRACT

The human body is a thermal system. It has the ability to generate heat invariably due to various biochemical reactions and the ability to regulate temperature by various thermoregulatory mechanisms. Malignancy on the other hand increases the metabolic activity of cells and augments the heat generation process featuring local thermal imbalance. Indeed, the rate of heat generation and heat dissipation are uneven, causing the local temperature of malignant tumor to rise. The increase in local temperature of tumor exhibits thermal contrast in the

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thermogram individuating the diseased and healthy region when imaged using a thermal camera. Over the last few decades, infra-red thermal imaging methods were highly admired due to their ability to detect functional changes and early traces of cancer. In fact, the methods such as dynamic thermography, active thermography, passive thermography and infrared transillumination techniques exhibited high sensitivity for breast cancer diagnosis. Moreover, these methods are proven to be useful to monitor growth of the lesion as well as responses to the treatment. This chapter aims to review various infrared thermographic methods, viz., dynamic and steady state, passive and active methods for the detection of malignant lesion in breast and skin. It also discusses the suitability of these methods for differentiating the malignant lesion from the benign one. The recent advancements in the field which include the role of heat transfer models and inverse modelling/thermal tomography for predicting the location, stage and size of the cancerous tumor are illustrated. Finally, future research directions are suggested.

Keywords: thermal imaging, skin cancer, breast cancer, medical diagnosis

1. INTRODUCTION

Currently, there are a wide variety of medically approved non-invasive techniques used for the detection of tumors and traces of cancer in the tissues. These techniques, viz., X-ray, computed axial tomography (CAT), magnetic resonance imaging (MRI), positron emission tomography, ultrasound imaging, thermal techniques and optical techniques, are highly admired by the medical practitioners due to its ability to provide a crucial contribution to the diagnosis of cancer [1-7]. In many situations, these methods reveal more objective and quantitative details which remain unwrapped in the pathological tests. Moreover, non-invasive methods are quite useful for pre- and post-clinical diagnosis as well as prognosis because these are faster and can be used repetitively for longer span with slight risk of radiation exposure in certain cases. These techniques are based on forms of energy, viz., electromagnetic and particle radiation, sound waves or magnetic fields, that are attenuated by bio-fluids, living soft and hard tissues during its flight through the body. The observed changes in the energy pattern or the image contrast indicate evidences of abnormal conditions which require thorough knowledge and careful observations.

Conventional non-invasive techniques, viz., X-rays, Ultrasound, and CAT scans are quite reliable for the identification of shape, size and location of tumor but are rated low for early detection of cancer. One of the reasons being the fact that these techniques lack the sensitivity to the functional changes. Further, the high cost associated with handling these scanners limits their use. Interestingly, even after using contrasting agents, these techniques are only capable to detect malignant lesions once the cells grow into a single mass/tumor of approximately 1 cm^3 [1]. For example, X-rays of lung and breast are commonly used to locate abnormal tissue/tumors, which demand further invasive investigation of the suspected area to discern cancerous and non-cancerous lesions. CT scans on the other hand, can produce detailed images with better resolution compared to X-ray but lacks the ability to identify cancer in soft and sparse tissue without any contrasting agents. The contrasting agent, i.e., iodine used for CT scan often cause side effects such as allergies and kidney problems [8]. It is ten times more costly than standard X-rays and produces shadow like images which are difficult to analyze at times. Moreover, the energy sources being used in these techniques are forms of radiation that can ionize tissue and can be harmful if used too often for longer duration. Ultrasound uses 1 to 10 MHz sound waves to locate abnormalities in soft tissues, and is capable to distinguish fluid filled cysts from solid tumors. However, it lacks the ability (a) to discern malignant from benign tumor and (b) to penetrate the imaging depth more than 10 cm for most organs [1, 9]. MRI on the other hand is a powerful technique with sub-millimeter spatial resolution and is capable to give better images of soft tissues which are hard to identify by other imaging techniques [1]. MRI with the help of contrasting agent can help doctors distinguish a non-cancerous tumor from a cancerous tumor. However, MRI is quite expensive compared to other methods due to high cost associated in running superconducting magnets. For about 30-45 minutes, and sometimes up to two hours in a fixed position, the patient is constrained to bear with the high noise inside the machine. Symptoms of headache and nausea are observed in patient due to the above mentioned factors. Similarly, other advanced diagnostic techniques such as nuclear medicine imaging/positron emission tomography are based on radiopharmaceutical application. It has the ability to provide detailed three dimensional images indicating physiological as well as functional changes in tissues and can play important role in pre- as well as post-clinical diagnosis. But it exposes the body to radioactivity that is potentially harmful, although unproven it has a slight risk of inducing cancer. Moreover, the use of high cost cyclotrons needed for its operation makes it very expensive, and are not easily available because of the need for careful handling.

Current medical status indicates that prevention is one of the most important cancer fighting tools compared to curing. Thus, it is important to detect the cancer as early as possible before it spreads. Conventional techniques, viz., X-ray, CT/CAT scans and ultrasound, are quite efficient at knowing the presence, location, and size of a large tumor mass, but fails to confirm early signs of cancer and various prognostic features. Indeed, many clinical cases confirmed that by the time these techniques could detect and differentiate the mass, often the disease has already spread [9]. The reason being the dependency of these techniques for ascertaining the structural variations of tumor from surrounding tissue. Further, these methods were not used in simple clinical setting and thus lead to delay in detection. Additionally, these imaging techniques are expensive, and sometimes produce unacceptable images that lead to significant cases of false negative and false positive results. Thus, there is a need to explore other non-invasive tools and techniques which should be cheaper, effective, easy to handle and convenient for patients. Thermal imaging is one such alternative method which detects the temperature variation due to (a) abnormal vascular flow and microcirculation of blood attributing to the launch and progression of lesions and (b) physical changes in tumor size and penetration depth. Indeed, in practice the thermal imaging technique is filling the gap in clinical diagnosis where structural changes are insignificant and physiological and/or metabolic changes are significant. In fact, in the past medical thermography had revealed few early features 8-10 years before the clinical detection of cancerous lesion using conventional techniques.

This chapter aims to review the vast area of thermal imaging techniques, focusing on their ability to detect cancerous lesions and differentiate from benign lesions found in the skin and breast. At first, a brief description of the facts and figures about skin and breast lesion is discussed. Next, a detailed account of various studies and findings obtained from medical thermography of skin and breast cancer is presented. Finally, the chapter focuses on various categories of medical thermography, the recent advances, and the future directions.

2. BACKGROUND

2.1. Cancer Facts and Figures

Malignant cells are transformed form of normal cells which are originated due to mutation in genetical composition [10]. The malignancy alters the usual cellular signals, and thereupon refrain any changes due to the active immune system. These cells are capable to replicate faster in an uncontrollable manner assisted by an increase in the metabolic activities [11]. It can invade adjacent native as well as non-native cells, and sometimes spread to other locations of the body via lymph and blood.

Malignant lesions of skin and breast are commonly found among the patients in the United States (US) and around the world. According to the National Program of Cancer Registries (NPCR), US [12] during 1999-2007, the skin cancer has remained the sixth and the seventh common types of cancer found in male and female population, respectively. The breast cancer, on the other hand, was having the highest incidence rate in female compared to other types of cancers. Figure 1 depicts the age-adjusted incidence rate of different types of cancer in female and male during 1999-2007.

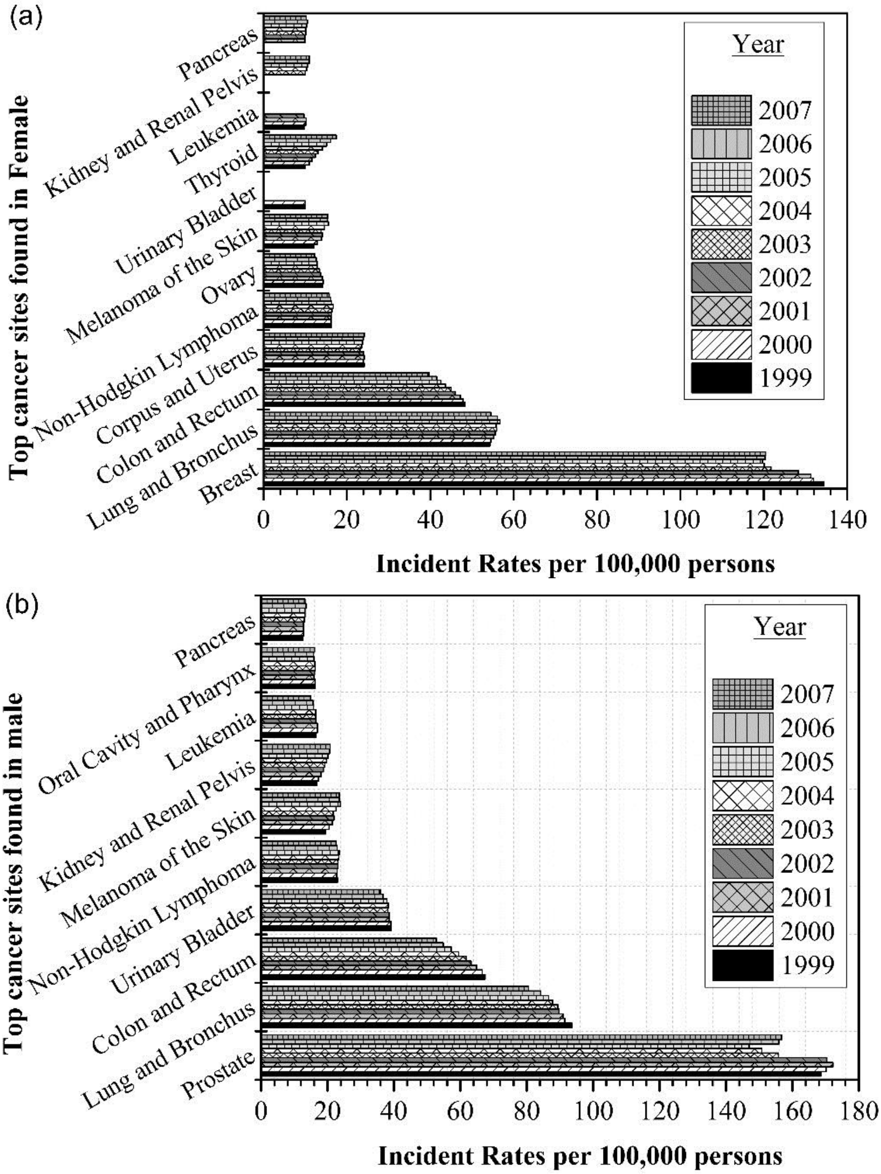
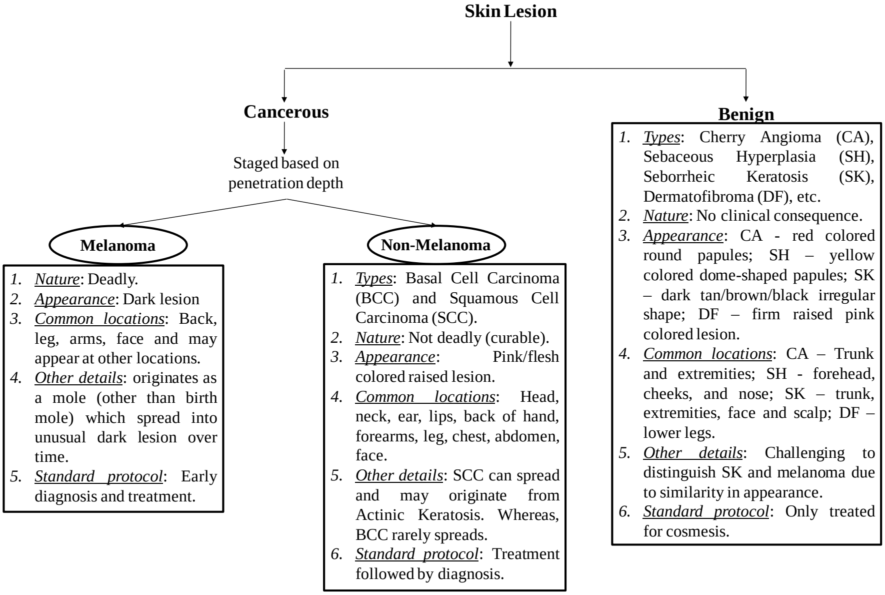


Figure 1. Age-adjusted incidence rates of top cancer sites found in (a) the female and (b) the male of all races (Data acquired from the National Program of Cancer Registries [12]).



Melanoma

1. *Nature*: Deadly.
2. *Appearance*: Dark lesion
3. *Common locations*: Back, leg, arms, face and may appear at other locations.
4. *Other details*: originates as a mole (other than birth mole) which spread into unusual dark lesion over time.
5. *Standard protocol*: Early diagnosis and treatment.

Non-Melanoma

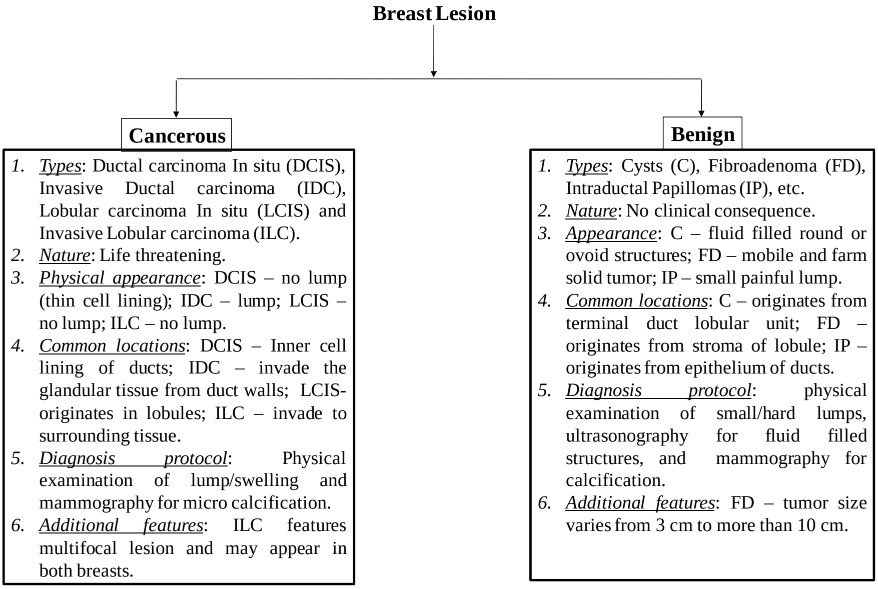
1. *Types*: Basal Cell Carcinoma (BCC) and Squamous Cell Carcinoma (SCC).
2. *Nature*: Not deadly (curable).
3. *Appearance*: Pink/flesh colored raised lesion.
4. *Common locations*: Head, neck, ear, lips, back of hand, forearms, leg, chest, abdomen, face.
5. *Other details*: SCC can spread and may originate from Actinic Keratosis. Whereas, BCC rarely spreads.
6. *Standard protocol*: Treatment followed by diagnosis.

Benign

1. *Types*: Cherry Angioma (CA), Sebaceous Hyperplasia (SH), Seborrheic Keratosis (SK), Dermatofibroma (DF), etc.
2. *Nature*: No clinical consequence.
3. *Appearance*: CA - red colored round papules; SH – yellow colored dome-shaped papules; SK – dark tan/brown/black irregular shape; DF – firm raised pink colored lesion.
4. *Common locations*: CA – Trunk and extremities; SH - forehead, cheeks, and nose; SK – trunk, extremities, face and scalp; DF – lower legs.
5. *Other details*: Challenging to distinguish SK and melanoma due to similarity in appearance.
6. *Standard protocol*: Only treated for cosmesis.

Figure 2. Common cancerous and non-cancerous skin lesions with their features.

In general, skin cancer originates at the epidermal-dermal junction or in the dermis of the skin, which were named after the type of cells. It is categorized into melanoma and non-melanoma. Further, based on the appearance, the skin lesions are also distinguished as pigmented and non-pigmented lesions. Among all types of cancers, the melanoma metastasizes rapidly, causing the majority of the deaths and target soft tissues like lung and the liver [13]. This is mainly due to the fact that skin has access to both nearby lymphatic systems as well as blood vessels. It is commonly staged based on superficial penetration depth within the skin, and the size which may vary from less than 1 mm to greater than 4 mm [13]. Further, skin lesions can be non-cancerous/benign, which are often difficult to distinguish from cancerous lesion due to similarities in their appearance [14]. Figure 2 depicts the selected skin lesions and their features.



Cancerous

1. *Types*: Ductal carcinoma In situ (DCIS), Invasive Ductal carcinoma (IDC), Lobular carcinoma In situ (LCIS) and Invasive Lobular carcinoma (ILC).
2. *Nature*: Life threatening.
3. *Physical appearance*: DCIS – no lump (thin cell lining); IDC – lump; LCIS – no lump; ILC – no lump.
4. *Common locations*: DCIS – Inner cell lining of ducts; IDC – invade the glandular tissue from duct walls; LCIS-originates in lobules; ILC – invade to surrounding tissue.
5. *Diagnosis protocol*: Physical examination of lump/swelling and mammography for micro calcification.
6. *Additional features*: ILC features multifocal lesion and may appear in both breasts.

Benign

1. *Types*: Cysts (C), Fibroadenoma (FD), Intraductal Papillomas (IP), etc.
2. *Nature*: No clinical consequence.
3. *Appearance*: C – fluid filled round or ovoid structures; FD – mobile and farm solid tumor; IP – small painful lump.
4. *Common locations*: C – originates from terminal duct lobular unit; FD – originates from stroma of lobule; IP – originates from epithelium of ducts.
5. *Diagnosis protocol*: physical examination of small/hard lumps, ultrasonography for fluid filled structures, and mammography for calcification.
6. *Additional features*: FD – tumor size varies from 3 cm to more than 10 cm.

Figure 3. Common cancerous and non-cancerous breast lesions with their features.

Breast cancer, on the other hand, originates in the inner cell lining of terminal duct of the lobular unit, which later spreads to the surrounding tissue [13]. Breast cancer is staged based on location, invasion, and tumor dimensions. It commonly metastasizes to bone, lung, liver, and brain through lymphatic and blood vessel network. The size of breast tumors may vary from less than 2 cm to greater than 5 cm [13]. The diagnosis of breast cancer relies on either physical examination of lumps or swelling of lymph nodes under the armpit and/or mammography for possible sign of calcification. On the other hand, the benign lesion has a similar physical resemblance as that of cancerous lesion and are hard to be distinguished using mammography and/or ultrasonography [15]. Figure 3 depicts commonly found breast cancer and benign breast conditions and their features.

2.2. Infrared Thermography for Detection and Differentiation of Breast Lesion

Late 1950 saw the advent of a new medical diagnostic procedure, infrared imaging technique, which has gained exceptional interest in breast cancer imaging, followed by various military applications. Initial thermographic observations revealed that local temperature of cancer affected tissue is a few degrees higher compared to the surrounding normal tissues, which is marked as hotspot assisted by asymmetrical vascular pattern in the thermogram [16]. Later, Lawson and Chughtai [17] observed that the temperature of venous blood leaving the malignant site is higher than the temperature of arterial blood flowing in, and suggested that venous convection increases the skin surface temperature near the malignant lesion. Further, infrared findings affirmed that vascular proliferation enhances metabolic rate followed by convection heat transfer due to increased vascular flow, along with the capability to identify hyper-vascularity and hyperthermia in breast cancers [18].

Consequently, in 1993 infra-red findings revealed impartial and quantitative details, and correlated various prognostic features observed in the breast cancer based on dynamic analysis and real-time image interpretation [19]. Especially, the quantification of microvascular density or vascular growth featuring angiogenesis revealed various prognostic attributes, viz., tumor size, grade, and lymph node status, etc. A study by Guido and Schnitt [20] suggested that, angiogenesis is an early event in the development of breast cancer, before the observance of any mass accumulation in the breast. Later Keysjerlingk et al. [21] reported the unique ability of thermography to detect early warning signals (about 8-10 years) ahead, before mammography can detect a tumor in the breast. On the other hand, couple of investigations [22, 23] introduced an approach to identify differences between a malignant and benign tumor using thermography. It was concluded that, in order to better differentiate breast malignancy from benign breast lesion, thermography should be done during thermal recovery after cold stress. The study revealed that vascular pattern disappears in the breast thermogram under cold stress, and reappears gradually after removal of cold stress. This important specification led to the use of dynamic breast thermography, which is capable to identify even small tumors not visible in steady-state thermogram [24]. In general, the effectiveness of breast cancer thermography is quantified based on two parameters: (a) by its sensitivity to detect cancerous involvement before the operation and (b) the specificity with which it can ascertain and/or discard the findings. In fact, many earlier studies revealed that thermography can achieve a high level of sensitivity (70-95%) and specificity (> 90%) in breast cancer diagnosis compared to mammography [6]. Likewise, studies have also revealed significant cases of false positive and false negative results for breast cancer diagnosis using thermography [6, 25].

Overall, many positive and negative views were presented regarding the accuracy of medical thermography for detection and differentiation of breast malignancy [6, 25-27]. These views led to a few important conclusions regarding breast thermography:

1. It can highlight early signs of malignancy marked by abnormal breast thermogram. The abnormality in thermogram is represented by hyper- and hypothermic textured areas featuring an increase or decrease in local microcirculation and metabolism. In fact, the progressive thermographic abnormalities observed in thermograms taken at different dates are clear indications of malignancy. Further, it is evident (from Figure 3) that breast cancer often originates as a thin cell lining and its presence can be revealed based on functional imaging similar to thermography.
2. Breast consists of dense tissue. Hence, thermography alone cannot tell the location and grade of a tumor. However, thermography in combination with other diagnostic methods, viz., mammography and ultrasound would lead to excellent predictability of cancerous and benign lesions. The location and size of solid tumor can be easily pointed out in a mammogram and/or ultrasound images. Further, thermogram can differentiate the cancerous and benign lesion based on the relative change in the temperature of hot spots.

3. Finally, there is a need for additional research on breast thermography with due consideration of large scale randomized studies. Further, it is important to revisit the major findings of breast thermography in the light of advancement in thermographic unit and image processing. The major focus is to frame guidelines for medical diagnosis of early cancer and differentiation of benign from cancerous tumor using a themographic or multi-modal unit.

2.3. Infrared Thermography for Detection and Differentiation of Cutaneous Lesion

From the early days of medical diagnosis, the skin temperature was related to index of abnormality. It was in 1964, Brasfield and colleagues [28] realized the role of thermography for detection of cutaneous melanoma. Later, the potential of thermography for melanoma diagnosis and prognosis was investigated by Gross et al. [29] and by Millard and Hesseler [30]. During 1969-1984, a series of studies on patients were conducted in Europe to determine the usefulness of thermography for diagnosis and prognosis of cutaneous melanoma. In fact, two different views were presented by different groups. A group from Cancer Institute, Marseille, France [31] suggested infrared thermography is a useful adjunct tool for diagnosis of cutaneous tumor, determination of spread (metastases), the prognosis of invasion, and for monitoring the effects of treatment. Their study also laid down a system of classification for medical thermography of cutaneous lesion based on the rise in temperature of the lesion above healthy region on the thermogram. On the other hand, a group from Italy [32, 33] regarded thermography as a useless method for diagnosis of cutaneous melanoma. Their study revealed 61.5% false negative results for cutaneous melanoma less than 0.76 mm thickness and 22% false positive cases. These views led to few important facts regarding medical thermography of cutaneous lesion such as

1. Local temperature gradient < 1 °C in raw thermogram is generally regarded as benign lesion. Thermography fails to distinguish melanoma from that of the benign lesion, having penetration depth < 0.76 mm also featuring local temperature gradient < 1 °C.
2. Local temperature gradient between 1-3 °C in the raw thermogram is regarded as a low grade malignant lesion. On the other hand, temperature gradient between 2-4 °C is considered as a high grade malignant lesion. In fact, the higher penetration depth of lesion led to greater chances of being hot. The extension of temperature gradient beyond the apparent boundary of clinically visible lesion signifies probable cases of metastasis. In such situation, thermography should be extended to locate secondary locations of melanoma spread (commonly observed secondary locations are depicted in Figure 2) for possible hyperthermic region in the range of 1-2 °C.
3. Thermographic prognostic factor relates the degree of local hyperthermia to the length of survival. In general, cold melanoma < 1 °C has a high survival rate. On the other hand, hot melanoma (~ 1 - 4 °C) showing thermal spread has highest death rate. Thermographic follow-up pointed out that (a) after excision of lesion, the region of interest should cool down to isothermic condition within a month, and (b) after radiotherapy the region of interest remains hyperthermic for two months but gradually cools to isothermic condition later.
4. The source of false negative results during thermography is due to ulceration, exudation, necrosis, and slow growing tumor, and that of false positive results are benign pigmented lesion, physiologic hot region, infections and angiomatous abnormalities.

Various evidences of thermographic investigations revealed irregular local hyperthermic and hypothermic regions featuring the effect of tissue local microcirculation and metabolism. Thus, suppressing the thermal contrast of small/early melanoma (< 0.76 mm thickness) in the raw thermogram. In order to detect a small melanoma, temporal variation of raw thermogram is a promising approach to highlight small melanoma and reject the effect of microcirculation occurring at different depths. Indeed, due to mismatch in thermophysical properties of features, viz., lesion and blood vessels, the thermal pattern corresponding to each feature would reveal at the surface of the skin at different times. In 1995, Di Carlo [34] applied the dynamic thermographic method for medical diagnosis of cutaneous lesion. Di Carlo's method was an improvement to the existing steady state thermography, which had failed to detect cutaneous melanoma < 0.76 mm thickness. A cold and hot contact type thermal stimulation was applied to the skin surface using a balloon filled with thermostatic alcohol-water solution. The idea was to reduce the temperature of the skin and the cutaneous lesion below a certain value for 20 seconds (cold stimulation), and then impose hot stimulation for 20 seconds on the skin for fast recovery from cold stress. During this recovery period, malignant cutaneous lesion quickly appeared as a hot spot in comparison to the surrounding normal tissue due to mismatch in the thermophysical properties. Hence, the method is suitable to discern the small malignant lesion even in a physiologically hot region. The study also suggested that pigmented benign lesions exhibit constant hypothermic condition after the thermal stimulation. Later, Cetingul and Hermann performed the same experiment for the detection of cutaneous melanoma [35]. However, in this method, thermal recovery period was attained by allowing the skin to recover under ambient condition instead of using hot stimulation. Very recently, Godoy et al. [36] showed that dynamic thermal imaging during thermal recovery from cold stress could lead to high level of sensitivity in skin cancer diagnosis and specificity to distinguish benign from malignant lesion. The method was based on the classification of lesions, viz., malignant/benign from normal tissue by comparing the recovery curve of pixels that are at the same initial temperature. The idea was based on the fact that lesions and normal tissue have different thermophysical properties, and were cooled to a different temperature during application of cold stress. Thus, two different thermal recovery curves were revealed. However, selection of uniform initial temperature would allow correct comparison of recovery of lesion and normal tissue. To distinguish the cancerous and benign lesions two thresholds were defined featuring the difference between the average thermal recovery measured across the suspected region and the average thermal recovery measured outside the suspected region. The study included 102 subjects, and later the biopsy results affirmed 59 subjects with benign lesion, 29 subjects with Basal cell carcinoma, 8 subjects with Squamous cell carcinoma and 6 subjects with melanoma.

2.4. Principles of Medical Thermal Imaging and Its Advantages

The infrared (IR) radiation falls within the wavelength range of 0.7-1000 µm (or having a frequency range of 430 THz to 300 GHz). All objects emit IR radiation when the temperature is above the absolute zero. It is a well-known fact that the core temperature of the human body is always above the absolute zero, i.e., in the range of 36.69 - 37.2 ^{o}C [37], due to the associated metabolic and physiological activities. As a result, the peripheral human skin temperature also remains above the absolute zero and emits IR radiation within the far infrared spectral range of 2.5 µm to 13 µm or above depending on the environmental thermal configuration [38]. Human skin behaves similar to a black surface within the mentioned spectral range, and having emissivity close to unity [38, 39]. The spectral radiance E_λ from the skin surface in thermal equilibrium is defined by the Planck's law as

$$E_{\lambda} = \varepsilon(\lambda) \times 2\mathrm{hc}^2 \lambda^{-5} \left[\exp\left(\frac{\mathrm{h}c}{\kappa_B \lambda T} \right) - 1 \right]^{-1} \tag{1}$$

where ε is the spectral emissivity, h is the Planck's constant, c is the speed of light, κ_B is the Boltzmann constant, λ is the wavelength and T is the temperature. Here, Eq. (1) correlates the spectral radiance of a perfectly black body ($\varepsilon = 1$) or a gray body ($\varepsilon \neq 1$), which is a function of wavelength. In fact, for a given temperature, the radiant energy is emitted by the body in a range of wavelengths. However, the total energy emitted by the surface correlates with the area under the curve representing the spectral radiance from a surface (Eq. (1)) at a particular temperature and can be approximated by Stefan-Boltzmann law as

$$E_T = \int_0^\infty E_\lambda \, d\lambda = \sigma T^4 \tag{2}$$

where σ is the Stefan-Boltzmann constant.

It is worth-mentioning that, the detector of a thermal camera is capable to detect within a particular wavelength band and it cannot detect the radiance for a whole spectrum of wavelength. Therefore, relating the total radiance (Eq. (2)) for camera detection may lead to small but undue error. In general, the spectral radiance $E_{\lambda,cam}$ received by a thermal camera is the summation of the radiance emitted by the skin surface $E_{\lambda,skin}$ and the radiance contributed by the surrounding environment, $E_{\lambda,env}$ and other heat source. Therefore, the spectral radiance received by a camera $E_{\lambda,cam}$ can be expressed as

$$E_{\lambda,cam} \approx \varepsilon(\lambda)\tau(\lambda)E_{\lambda,skin} + \left[1-\varepsilon(\lambda)\right]\tau(\lambda)E_{\lambda,refl} + \left[1-\tau(\lambda)\right]E_{\lambda,env} \tag{3}$$

where τ is the spectral transmitivity of the atmosphere and $E_{\lambda,refl}$ is the reflected portion of the radiation from the skin surface due to radiation emitted by other sources. Figure 4 depicts the graphical illustration of the radiation received by a thermal camera.

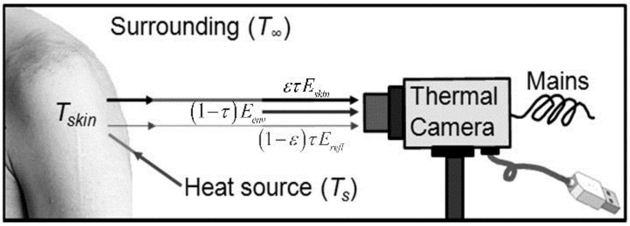


Figure 4. Schematic representation of radiant energy received by thermal camera.

Few studies have also shown that, a favorable wavelength range (8–10 μm) exists for the thermal evaluation of the skin, since IR radiation from the skin surface exhibits a maximum peak within this wavelength range [40]. This can be easily confirmed by the Wein's displacement law

$$\lambda_{\max} = 2897/\mathrm{T}_{skin} \tag{4}$$

where λ_{max} is the wavelength corresponding to maximum radiance and T_{skin} is the temperature of the skin surface in K. Apart from the above facts, the IR radiation exhibits nearly 100% transmittance through the atmosphere/ air ($\tau = 1$) within the spectral range of 8-10 μm [41]. Hence, it is evident that measuring the skin IR radiation within the spectral range of 8-10 μm is advantageous. In fact, if measurement is carried out in the absence of any other heat source ($E_{\lambda,refl}$), then Eq. (3) will reduce to

$$E_{\lambda,cam} \approx \varepsilon(\lambda) E_{\lambda,skin} \tag{5}$$

Here, the effect of environment on the sensitivity of the camera can be neglected since transmitivity of the atmosphere is unity in the above mentioned spectral range. Therefore, the surface radiance can be assumed to be nearly equivalent to the radiance received by the camera. The above analogy and the statement are true, only if the radiance from surrounding is insignificant. Indeed, it is a standard protocol to carry medical thermography in an isolated room away from any heat source to avoid camera calibration and measurement error. By considering the theoretical relations and proper calibration, the radiometric values received by the camera can be converted to a temperature value indicating the exact surface temperature.

The thermal imaging techniques are highly admired by the medical practitioners due to various advantages: (a) non-invasive and non-contact method, (b) easy to handle, (c) portable, (d) painless, (e) fast, (f) no harmful radiation effects, (g) cost favored, (h) highlights important thermo-physiological processes that are not understood well by the other techniques, (i) useful for pre- and post- clinical evaluation since these techniques can be used repetitively for longer time span with no radiation risk, etc.

3. CLASSIFICATION OF THERMOGRAPHY

3.1. Transillumination Technique

Transillumination technique is an alternative diagnostic method which uses visible, near infrared or red light source in a dark room to identify subsurface lesion and/or anomalies within the breast by monitoring the transmitted light. The transillumination of the breast using visible light in a dark room was first carried out by Cutler [42]. The study used the spatial resolution of transilluminated images and/or transilluminated videos to differentiate normal and abnormal breast tumors. According to Culter [42], the density difference between benign and malignant tumors led to variation in the degree of translucence, which could be an important protocol to differentiate these lesions. In fact, Culter also emphasized that differential diagnosis of breast tumors would require thorough knowledge of various anatomic details of malignant and benign tumors, such as accesses to lymph node or blood vessels and tumor growth over time. Figure 5 depicts a schematic diagram illustrating the transillumination technique.

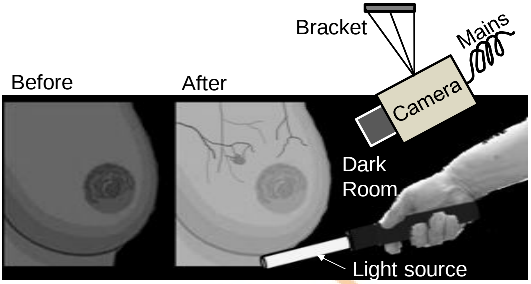


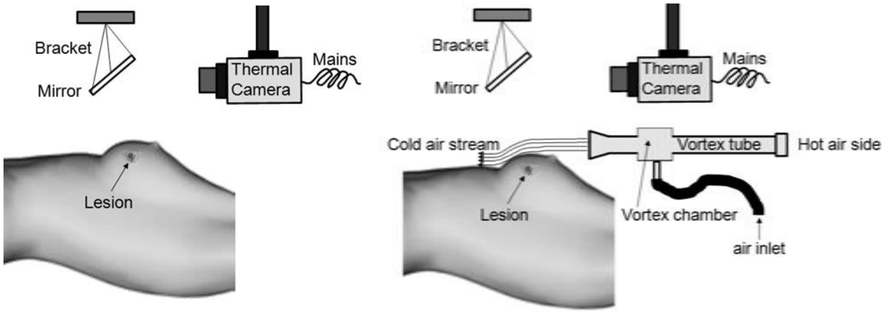
Figure 5. Artistic rendering of transillumination technique for detection of breast tumor.

Later, Gros et al. [43] coined a term diaphanography instead of transillumination and reported its possibilities to distinguish benign from malignant lesions using visible light. In 1980, Ohlsson et al. [44] revealed improvement in transillumination of cancerous lesion by photographing infrared wavelengths of transilluminated breast with an infrared-sensitive film. Further, Carlsen [45] followed by Bartrum and Crow [46], and later Merritt et al. [47] considered transillumination of the breast using near IR and red light source to identify real time anomalies by analyzing the variation in the transmitted light. Merritt et al. [47] performed a clinical study on 1,775 patients using infrared light and referred it as a useful diagnostic technique for breast diseases. The observations allowed them to categorize breast diseases such as (a) cysts appeared as a lighter area because of increased transmission of light, (b) vessels appeared darker due to higher absorption of light, (c) presence of dark mass represents a benign tumor, and (d) dark mass assisted by abnormal vascular patterns represents malignant tumors. The use of transillumination has shown considerable sensitivity for breast cancer detection, but completely loses its ability to identify deep body cancers, since red and near infrared wavelengths of visible spectrum exhibit heavy scattering and low absorption in biological tissue. Further, the projection imaging/transillumination technique is not practical to detect tumors in organs other than breast and testis since light fails to reach the detector through thick tissues. Consequently, the research interest in transillumination technique using visible and IR light slowly faded away due to subsequent blurring of images inherited by this technique. However, in this digital age, the application of projection imaging/transillumination technique could find its usefulness for quick inspection of any anomalies in the breast and testis in a simple clinical setting prior to mammography because it is easy to handle, fast and cheap. In fact, once installed it does not require any additional cost for performing tests. Indeed, the application of computer image processing and data analysis would further improve its sensitivity and specificity.

3.2. Passive and Active Thermography

Medical thermography is a non-invasive, painless, and functional imaging method, which quantifies the radiation emitted by the peripheral skin surface in the infrared region of the electromagnetic spectrum. Thermography involves mapping the temperature distribution on the surface to detect the subsurface anomalies. It can be classified into two categories, viz., passive and active modes. The passive and active modes of thermography enable one to identify the quantitative details of the subsurface features, viz., the variation in the thermal (properties of lesion) and the geometrical configurations (growth of the lesion), which appear as an identifiable temperature contour at the surface. The passive mode of thermography pertains to the thermal mapping without any external thermal stress or imaging for internal heat source such as a tumor [16]. In fact, the thermography of the human body due to internal stress also falls in this category. For example, thermography after exercise. Most of the earlier investigations used passive thermography for the detection of cancer in breast [16, 17]. Indeed, the accuracy of this detection method depends on various protocols used for examination [48]. Few important protocols are: (a) the position of the camera relative to the patient should be kept constant during the examination, (b) measurement should be carried out in a dark room with a low light source to avoid the effect of background light as discussed earlier, (c) the room temperature should be below the body temperature, (d) the room temperature, humidity and surrounding air velocity should be maintained constant, (e) the patient should acclimatize to these conditions prior to the measurement, etc. Overall, the passive method has shown high senstivity and specificity in the detection of subsurface cancerous lesion [6]. However, the method was not used for the differentiation of cancerous lesion from benign lesions. In practice, benign lesions are marked as solid lumps with negligible metabolic activities. Naturally, a palpable solid lump with no contrast in the thermogram over time can be identified as a benign lesion.

In the active mode of thermography, on the other hand, an external energy source/thermal stimulation, viz., cooling [24, 35, 49] or heating [50, 51] is applied to map the surface thermal response. In fact, the active mode often leads to better contrast and resolution for the detection of subsurface anomalies compared to passive mode due to controlled external thermal stimulation. In many situations, the passive mode lacks the contrast since the feature is already in thermal equilibrium or the feature temperature is less than the skin surface. Whereas, the active mode is a useful approach, especially when the feature is already in thermal equilibrium with the surroundings. The commonly known effective active thermography methods for detection and differentiation of cancerous lesions are IR imaging during thermal recovery from cold stress [24, 34-36] and lock-in-thermal (LIT) imaging [49]. These methods are elaborated in the next section. Further, the active modes featuring heating of skin surface instead of cooling are less popular methods in medical thermography. The reason being (a) the poor thermal contrast (as feature temperature is less than the surface temperature), (b) the shallow penetration of thermal wave, and (c) negligible thermal diffusivity of biological samples. It is worth-noting that, passive and active thermographies are further classified as steady state and dynamic thermographies. A schematic diagram to represent the working principle of passive and active mode of thermal imaging techniques were depicted in Figure 6.



Passive Thermography

Active Thermography

Figure 6. Schematic diagram representing (a) passive thermography of breast lesion (no thermal stimulation) and (b) active thermography of breast lesion (cold stimulation).

3.3. Steady State and Dynamic Thermography

The steady state thermography (SST) refers to the case when a single image is taken during the evaluation. The single thermal image is taken when the test surface approaches a thermal equilibrium/steady state condition and the patient's body has already acclimatized to the surrounding conditions. The focus is to identify the spatial variation and asymmetric temperature distribution in the thermogram due to subsurface lesion. In fact, the steady state thermogram of the same location taken on different dates is a useful strategy in the early days to detect and differentiate cancerous and benign lesions. The inherent idea was to compare the growth pattern of the lesion based on the variation in temperature distribution in the thermograms. Hence, an initiative was made to relate the observed variation and/or the change in thermal contrast in the steady state thermogram with the tumor size, depth from the surface, and *in vivo* blood perfusion [52-54]. The SST was also used for obtaining a thermal texture map based on reconstruction of cell's metabolic extent featuring abnormality [55].

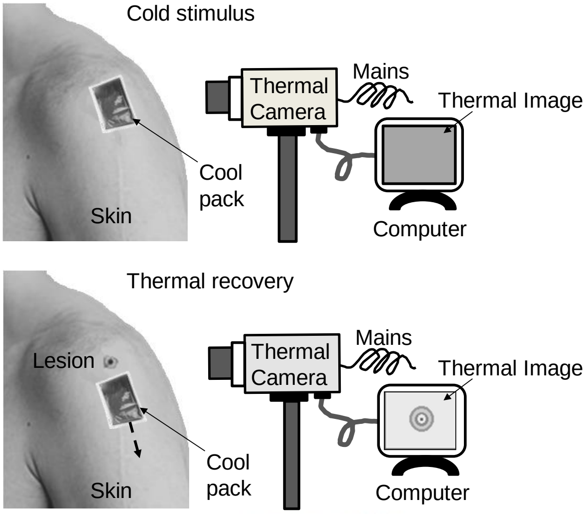


Figure 7. Schematic diagram representing the working principle of a dynamic thermal imaging method during thermal recovery from cold stress.

On the other hand, dynamic thermography is capable to quantify cancerous and benign lesions based on the spatial and temporal variations in the thermal contrast in a series of thermograms [36, 56]. Currently, a few popular dynamic thermographic methods are used for medical diagnosis of skin and breast lesion. For example, thermal imaging during thermal recovery from cold stress [24, 35, 49, 56] and lock-in-thermography [49]. Figure 7 depicts the schematic representation of DTI method.

In dynamic thermal imaging (DTI) during thermal recovery from cold stress, the skin (or the patient) is initially kept in a stabilized ambient condition for 15-20 mins, so that the surface temperature reaches a steady value. Next, the surface and certain portions of the subsurface region are cooled below the reference steady value using a cold thermal stimulation for a short-period [35]. After a certain period, the cold stimulus is removed from the surface and the surface is allowed to recover to the reference steady value under the same stabilized ambient condition. During the thermal recovery period, the spatial variations of the temperature values on the skin surface are measured as a function of time using a thermal camera, indicating the differential changes in the thermal pattern between the abnormal region and the surrounding normal region. The observed temperature difference is mainly due to the thermogenic capacity, metabolism and blood perfusion of the lesion against that of the surrounding healthy tissues. In fact, the dynamic thermography is capable to reveal a small lesion, that remain undetected in steady state thermogram [22, 34]. Recently, Godoy et al. [36] suggested a unique strategy to differentiate cancerous and benign lesion using DTI method (discussed earlier).

The application of lock-in-thermal imaging for the detection of benign skin lesion was demonstrated by Bonmarin and Le Gal [49]. Later, the same method was also used for identification of early melanoma and its stages [57]. The LIT imaging method employed periodic cold and hot pulse excitations on the skin surface at a given frequency using a temperature-modulated airflow from a cooling unit, and simultaneously mapped the surface temperature at the same frequency using a thermal camera to generate raw thermograms and phase images. In principle, LIT method is superior compared to DTI since subtle changes in temperature gradient due to benign and early cancerous lesion would be visible in the phase images. The raw thermal images in DTI fail to differentiate the subtle changes due to the spurious thermal effect of local blood microcirculation and metabolism. Further, the LIT is a potential method for differentiation of melanoma stages (i.e., change in the penetration depth) based on associated phase differences.

4. RECENT ADVANCEMENTS AND FUTURE RESEARCH DIRECTIONS

4.1. Role of Theoretical Model and Inverse Detection in Medical Thermography

From the beginning of scientific exploration, mathematical models have been used to actualize the ideas and to predict the events in the dynamic world. In the present day scenario, the studies using models and computations help one to explain the effects and make the predictions about the outcome of complex biological interactions. It has slowly become an integral part of the biomedical research, which is being effectively utilized now-a-days to analyze the biological behavior and to estimate the optimal configuration. In fact, the simulation efforts serve as a means for refining the experimental protocols and thereby reduce the loss of resources due to poorly planned studies.

In practice, medical thermography only highlights the temperature gradient at the skin surface. Then, the observed variation in the thermogram, i.e., local hyperthermic and hypothermic region, was correlated to subsurface tumor and healthy region, respectively. On the other hand, the mixture of hyper- and hypothermic regions is correlated with the abnormality in the microcirculation and/or metabolism [34].

Further, based on any increase in the temperature above healthy region, thermography classifies cancerous and benign lesions [31].

However, medical thermography fails to reveal the clinically relevant information such as tumor depth, tumor size, microcirculation volume, and volumetric metabolism. In case of subsurface lumps, tumor size and tumor penetration depth are important features to stage malignant lesions. In fact, the knowledge of the above features is important for clinical practitioners to decide the course of treatment based on the level of seriousness. For example, the standard protocol to treat a low grade breast lesion having penetration depth < 1 mm is radiotherapy instead of excision, to avoid any spread. On the other hand, monitoring the variation of abnormal thermal texture featuring mosaic of hyperthermic- and hypothermic regions, would reveal the early signs of cancer. In general, the common clinical practice is to determine the structural changes, such as the size of the tumor by obtaining X-ray images or ultrasound images. However, in many situations X-ray images fail to provide correct information with the tissue being dense. Further, both X-ray imaging and ultrasonography fail to determine the functional changes such as the effect of increasing microcirculation and volumetric metabolism.

The above facts led to the use of the thermal tomographic method [52-54, 58-60] in medical thermography of cancerous lesion. In this method, the subsurface variation/anomalies were predicted using a combined effort of (a) theoretical model mimicking the heat transfer phenomenon in biological tissues and (b) data mining algorithm, based on the measured surface temperature. In fact, the theoretical models mimicking the heat transfer phenomenon in biological tissue was extensively used without the help of an inverse algorithm to optimize the operational conditions and for the prediction of disease diagnosis outcome [61-66]. Particularly in the 20th century, Feasey et al. [61] performed theoretical studies to determine the effect of natural and forced cooling on the thermographic patterns of the tumor. It was observed from the study that (a) the forced cooling at the surface demarcates the contrast of the subsurface hotspots, and enhances the contrast of the vascular pattern, (b) the surface temperature contrast reduces as the room temperature decreases, (c) a good contrast is possible at a comfortable room temperature and (d) the contrast at the surface mainly depends on the depth of the heat source, i.e., tumor. Later, Deng and Liu [62] used the Monte Carlo method to study the effect of (a) emissivity and humidity, (b) convective heat transfer coefficient, (c) relative humidity and temperature of the ambient air, (d) metabolic rate and blood perfusion in the tumor and (e) tumor size and the number, on the temperature map of the human skin. Wu et al. [63] studied the comparative changes in the skin surface temperature distribution caused by the variation of internal heat sources, environmental thermal configuration and physiological parameters. The study indicates that the depth of heat source can be determined theoretically from the full width and half height of the Gaussian temperature distribution curve. Similarly, variation of surface temperature distribution due to changes in the thickness of various skin layers and thermophysical properties was studied by Cetingul and Herman [64]. Based on the extensive parametric study, Cetingul and Herman suggested that the variation in the normal skin layer thickness and the thermophysical properties has negligible effect on the surface temperature. The study also pointed out that, among all the parameters, the variation in the skin layer thickness and blood perfusion exhibits a considerable change in the surface temperature. Further, it was concluded that the peak magnitude and the surface temperature profile of various skin lesions exhibit significant variations due to changes in the lesion geometrical parameters, such as width and depth of penetration. The effect of blood flow on the thermal response of the skin surface was investigated by Deng and Liu for the detection of tumor located in the vicinity of large blood vessels within the skin model using DTI technique [65]. The study demonstrated the thermal effect of larger blood vessels on the non-uniformity of the skin surface temperature. The study further suggested that the subsurface blood flow may lead to an error in the thermographic evaluation, and can cause false negative or false positive diagnoses during thermography. The reason being that, the nearby blood vessels overshadow the thermal effect of the lesion [66] in the steady state thermogram. In the above investigation [61-66], the Pennes bioheat equation [67] was used to predict the surface temperature due to associated boundary condition and subsurface thermophysical properties. In fact, the Pennes bioheat equation [67] was also used commonly for inverse detection of tumor size and characteristics.

As discussed earlier, in order to obtain a clinically relevant information, thermal tomographic methods or inverse methods are employed for the prediction of subsurface tumor features based on the temperature map obtained from a thermal camera. In fact, the accuracy of prediction depends on the choice of appropriate boundary condition on the surface of skin [53, 68]. It is also worth noting that, an inverse method is unable to provide a unique information due to its ill-posedness. Partridge and Wrobel [69] used dual reciprocity boundary element method for discretization of boundary and Genetic algorithm (GA) for inverse prediction of tumor size and location based on the surface temperature of the skin. The method demands only discretization of boundary and employ analytical function to represent the variation at the boundary points. It is also referred to as meshless method, and is suitable for problems, where a solution is required only at the surface. In fact, the prediction is faster when GA is coupled with the forward model due to non- requirement of internal nodes. Later, Bezerra et al. [70] predicted the blood perfusion and thermal conductivity of breast tissue by inverting the 3D bioheat model of layered breast using the Sequential quadratic programming (SQP) algorithm. Here, the measured maximum surface temperature in the thermogram corresponding to breast lesions (fibroadenoma and invasive ductal carcinoma) was fitted with the temperature predicted by the 3D bioheat model which used the inverse algorithm. In fact, the 3D model was constructed based on the anatomical details obtained from ultrasonography. The results revealed the possibility of accurately determining the thermophysical properties of breast and breast lesion using the present approach [70]. On the other hand, a faster inverse algorithm was developed by Han et al. [71] to predict the depth, basal temperature and thermal power of heat source in the breast. The study used the measured temperature data from thermogram of four female patients divided into two groups based on fatty breast and dense breast. Each group consists of two patients with benign and malignant lesion. The measured surface temperature data of breast in the region of interest was then fitted with the help of Levenberg-Marquardt algorithm to predict the thermal power, depth of the lesion, and basal temperature. Indeed, the forward model used here is the analytical solution of Pennes bioheat equation for polar coordinate system. The study revealed that the predicted value of power for malignant source is far greater than the benign source, and the results are independent of the type of breast.

On the other hand, Luna et al. [72] predicted the blood perfusion and tumor penetration depth of different stages of skin lesion using boundary element method and simulated annealing algorithm. The study assumed a 2D model for single skin layer with embedded tumor to obtain the surface temperature distribution. Next, the surface temperature distribution was fitted using simulated annealing inverting the same theoretical model to predict the blood perfusion and penetration depth of the lesion. Later, Bhowmik and Repaka [53] proposed a thermal system that is capable to simultaneously estimate tumor diameter, penetration depth, blood perfusion and metabolic heat generation by fitting the measured two dimensional pixel value of skin thermogram with the aid of data mining algorithms. The study considered the 3D layered model of human skin with tumor stages, Clark level II and Clark level IV, to determine the two dimensional surface thermal maps. At first, the forward model was validated with the measured data available in the literature. Next, two separate data mining algorithms were used, viz., genetic and simulated annealing algorithm to estimate the tumor features by fitting the two dimensional pixel values. The performance of simulated annealing was found to be favorable in terms of accuracy and time required for prediction. Indeed, the prediction of tumor growth feature was found to be faster than the standard biopsy result. The retrieved parameters displayed several sets corresponding to same skin surface map. Thus, indicates the possibility of benchmark thermograms for a range of tumor growth features and physiological attributes [53].

4.2. Future Research Directions in Medical Thermography

In future, thermography and IR transillumination technique may evolve as important methods for early detection of cancer in a simple clinical setting. In most cases, the early stage of breast and skin cancer regularly gets undetected in a simple clinical setting due to no lump formation and unavailability of the simple imaging system. Thus, a thermographic and/or IR transillumination tool would allow medical practitioners to gather first hand information regarding the abnormal feature in a simple clinical setting. In fact, the focus would be to monitor the asymmetry in hyper- and hypothermic textured regions on the steady state thermograms taken at different dates.

On the other hand, the combination of thermographic and structural diagnostic tools such as X-ray or ultrasonography may prove suitable for detection and differentiation of lump and metastasis in future investigations. Particularly, the size and location can be obtained using X-ray or ultrasonography. Whereas, the functional variations referring to changes in blood microcirculation and metabolism, regional node metastasis, metastases in transit, and metastases to secondary locations would be highlighted by a thermogram as hyperthermic regions.

Further, personalized thermographic devices, enabling patient to monitor any anomalies at home can find its application in future. In fact, due to rapid advances in bio-optics and microscale fabrication, it is possible today to fit a thermal sensor in a portable device such as cell phones. Moreover, in future internet may prove to be beneficial in medical diagnosis, allowing patients to upload the suspected thermal image remotely to an online repository. Indeed, such repository can be made automated to perform image manipulation or feature extraction using software to gather detailed information of the thermograms. The information gathered would bring awareness to the patients, and advice possible course of action without delay. This will eventually reduce the death rates due to breast and skin cancers, since these cases often remain unattended/untreated.

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Chapter 3

APPLICATION OF THERMAL IMAGING FOR THE ASSESSMENT OF BODY COMPOSITION IN HUMANS

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ABSTRACT

There is evidence that adipose tissue and muscle mass interfere with skin surface temperature, in humans. Infrared thermography may be used to analyze this variable, in health and biological sciences. This chapter is a review of literature regarding the relations between body composition and skin surface temperature (SST), measured with infrared thermography. Mostly, exceeding adipose tissue decreases SST, due to its

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thermal isolating action, which interferes with heat transfer between body and ambient. Subcutaneous fat thickness appears to be inversely related to SST in the same region, but it cannot be assumed for all body segments, since women's tricipital region hasn't showed the same result. Higher body fat percentages are also related to lower SST in thighs, abdomen and arms, for example. However, the opposite seems to happen in the hands, where SST increases when the individual presents a high body fat percentage. It is also possible to detect active brown adipose tissue with infrared thermography in the supraclavicular region, based on the increased temperature in response to cold stimuli. Muscle cross-sectional area is also a contributing factor for higher SST values. Some studies have showed significant results with linear regression with SST and body fat percentage, especially in women. The authors of this chapter enhanced this method by using infrared thermography in association with body circumferences, in young women. This model showed promising results, which can still be improved. It can be concluded that body composition interferes in skin surface temperature and it appears to be a useful variable to estimate body fat percentage, when environmental control is properly taken care of. Therefore, it is important that studies using infrared thermography, in several applications, consider the influence of the adipose tissue in its interpretations, since body fat may alter temperature results.

Keywords: Infrared thermography, Skin surface temperature, Body fat, Brown Adipose Tissue

1. INTRODUCTION

Several factors interfere in body temperature. Healthy humans tend to have core body temperatures close to 37°C. This value in maintained by several exothermic chemic reactions. Skin surface temperature (SST), however, is also influenced by other factors and it is lower than core temperature, near 33°C (Plowman and Smith, 2009). Since skin surface is in contact with the environment, SST depends on extrinsic factors such as air temperature, draughts and air humidity (Fernández-Cuevas et al., 2015). Therefore, controlled environments are required in order to an adequate estimation of SST.

Infrared thermography allows to assess surface temperature of bodies and objects by means of infrared radiation. This technology is frequently used in health and biological sciences, since it can precise SST in different body segments. Using thermal images, alterations in SST have been studied in order to analyze disfunctions caused by breast cancer, melanoma, temporomandibular disorder and diabetic foot, for example. However, very few information exists in literature about how human body composition may interfere in SST and, therefore, in several analysis with infrared thermography. It is known that exceeding body fat mostly reduces SST (Chudecka; Lubkowska; Kempińska-Podhorodecka, 2014), but this cannot be affirmed about every body segment (Neves et al., 2015a). Muscle mass appears to have the opposite effect in SST, increasing it (Neves et al., 2015b).

The aim of this chapter is to perform a review of literature regarding the use of infrared thermography, in two parts. In the first one, we expose the applicability of this method in medical diagnostics in humans. In the second one, we discuss about what is known, until this moment, about the relation between body composition and SST assessed with infrared thermography.

2. DIAGNOSTICS WITH INFRARED THERMOGRAPHY

Recently, a diversity of studies has been performed using infrared thermography as an alternative to diagnostics procedures and high cost technologies that may expose patients to risks, such as ionizing radiation. The diseases which are most frequently studied are different types of cancer, mainly breast cancer, in order to avoid discomfort and unnecessary exposure to ionizing radiation by usual mammography exams.

For this disease, particularly, several approaches have been tested attempting to otimize the efficacy of the infrared thermography technology in the diagnostics procedure. A research has been conducted aiming to sugest the use of thermal imaging as a method of diagnosing early breast cancer in large populations. In this sense, a sample of 1008 women have been evaluated and divided in groups according to the variation of SST of the breasts (difference of highest and lowest SST value). Those with variation higher than 2.5°C were considered in risk of developing cancer and the ones with variation higher than 3°C were considered to have breast cancer. Women from these two groups were submitted to mammography. The method showed good sensibility and specificity for malignant tumors, with values of 97.6% e 99.17%, respectively (Rassiwala et al., 2014).

Sella et al. (2013) have also published about breast cancer, using a three dimension analysis with infrared thermography. Their study has been designed in two phases, of which the first one was training and calibration, which consisted in searching for the best algorithm according to vascularity and dimensions. The second one was a double-blind study. In both these steps, healthy women were compared with women already diagnosed with breast cancer, who had tumors sized from 5mm to 45mm. In the first phase, sensibility reached 83% and specificity was 69%. In the second one, they increased to 90.9% and 72.5%, respectively.

Guerrero-Robles et al. (2015) have tested the possibility of differring benign and malignant tumors with infrared thermography. Thermal images were analyzed comparing patient's contralateral breasts, in order to identify whether the tumor was benign or malignant. The sensibility was similar to the mammography exam (70%), but the specificity was considerably lower, reaching 54% against 96%.

The validity of the method in diagnosing breast cancer was also compared to the tumor analysis in cytology and histopathology tests. This approach showed that, with infrared thermography, researchers were able to diagnose correctly 92% of the cases, even better than with the mammography exam, which diagnosed only 85% of them. With infrared thermography, a higher number of abnormality spots was detected, which led to a 100% sensibility and 79% specificity, against 85% and 84%, respectively, with mammography (Kolarić et al., 2013).

Although values of sensibility and specificity were, in most cases, high, in first stage tumors it has been showed differently. A research was conducted comparing ultrasound, mammography and infrared thermography in diagnosing primary breast cancers. Results showed 88% and 91%, 84% and 97%, and only 25% and 85%, respectively for sensibility and specificity with the cited technologies. In this study, SST of contralateral breast and of body parts near the breasts were used as parameters (Kontos; Wilman; Fentiman, 2011).

Based on the studies cited above, it is clear that the methods used to attempt to diagnose breast cancer with infrared thermography were very divergent. Therefore, patterns need to be established in order to clarify the effectiveness of the technology.

Melanoma is also a kind of cancer which has been studied with the aim of being diagnosed with thermal imaging. Compared to a high-frequency ultrasound, infrared thermography showed 28.8% of sensibility, while the ultrasound showed 100%. The advantage found in thermal imaging was that it did not show any false positive cases (Solivetti et al., 2014). Shada et al. (2013) found that infrared thermography was more effective in diagnosing melanoma when the lesions sized from 15mm to 30mm of diameter, showing sensibility of 95% and 100% specificity. In lesions both smaller or bigger than these, specificity was higher than sensibility, but both were lower than the results of that specific size.

Besides cancer, other diseases were studied with infrared thermography as a way to have them monitored and diagnosed. Van Netten et al. (2013), studied foot ulcers caused by diabetes mellitus. Significant differences were detected between the temperatures of the affected foot and the contralateral limb. Although it had a different approach, this data agrees with the results found by Barriga et al. (2012). The referred author showed that healthy individuals recover foot temperature more easily than those with diabetic foot, after cold stimuli. Similarly, Huang et al. (2011) studied peripheral arterial disease and concluded that those affected by this dysfunction lose heat after exercise, showing decreased SST of the foot, while healthy people tend to gain heat in the same situation.

Medina-Preciado et al. (2014) and Hardwicke et al. (2013) described the severity of burn wounds, with infrared thermography. Both studies showed decreased SST in higher degree burns. Superficial burns, however, may have similar (Hardwicke et al., 2013) or higher (Medina-Preciado et al., 2014) SST than healthy tissue.

Apart from diagnosing and monitoring diseases, infrared thermography was also tested in other ways, such as aiming to improve other existing technologies. Sanches et al. (2013) attempted to associate magnetic resonance imaging, computerized thomography and infrared imaging. The aim was to help to detect the anatomical sites, which is not possible with infrared thermography, and to associate them with the physiological changes found in thermal imaging. This model with three technologies, however, was not tested in several individuals, in order to show practical results in health sciences.

In sports sciences, Carvalho et al. (2012) used thermal imaging to describe the actual decrease in SST as a result of cryotherapy. The preferred method is used as a way of preventing from lesions, by applying ice on the limb where a muscle might be sore. Infrared thermography was also applied in other studies with athlete subjects, by searching for relations between SST and the concentration of blood creatine kinase, after a training session. Increased creatine kinase might indicate an inflammatory process, which may be caused by inadequate sports training. Both variables tested were showed to be increased, but they were not correlated with each other. This result was found both for soccer players (Bandeira et al., 2012) and rugby players (Bandeira et al., 2014).

Still, in healthy subjects (Al-Nakhli et al., 2012a) and in diabetic patients (Al-Nakhli et al., 2012b), increased SST, assessed 24 hours after training of dynamic strength, was found to be related with increased serum myoglobin, in researches concerning delayed muscle soreness. After 48 hours, however, the concentration of serum myoglobin remained high, while the SST in the exercised limb decreased to levels similar to the moments pre-exercise. In conclusion, authors believed that infrared thermography would only be effective in identifying the first stages of delayed muscle soreness.

It is important to highlight that, in those studies concerning breast cancer and others diseases and dysfunctions, physiological changes occur below the hypodermis, i.e., below the adipose tissue. For that matter, the insulating barrier action of the fat mass might have hinderred the heat transfer through skin, in each case. Since, in those studies, the body composition was not controlled, it is not possible to infer whether the samples were homogenous in terms of body fat and, consequently, whether individuals might have had their SST reduced, masking their syntoms, when analyzed with thermal imaging.

3. INFRARED THERMOGRAPHY AND BODY COMPOSITION

Although it is an unexplored theme, there are already studies, in literature, which analyzed human beings and searched for relations between body composition and SST, assessed by means of infrared thermography. Body composition is affected by lean mass and fat mass. The adipose tissue may be present in two different ways, in human body, both already assessed with thermal imaging: white adipose tissue, which consists of the commonly studied fat depots of subcutaneous fat or visceral fat; and brown adipose tissue, which is present mostly in babies and children, but may also be present in adults, in the supraclavicular region. The first one may lead to several diseases, if it exceeds in human body, while the second one has important metabolic function (Cypess et al., 2009).

Jang et al. (2014) showed, in their study, that the presence of brown adipose tissue, assessed by means of Positron Emission Tomography (PET), results in higher SST in the supraclavicular region, after a two-hour exposure to an environment with 19°C. These results, however, were found observing the increase of SST without statistical significance. Besides, the volume of brown adipose tissue did not correlate with supraclavicular SST. This study included subjects with large differences in body mass index, without considering that there might be discrepancies in the concentration of brown adipose tissue found in normal weight and obese individuals. Therefore, it is not possible to infer whether subcutaneous fat or body fat percentage interfered in the analysis.

Robinson et al. (2014) studied children, aiming to identify brown adipose tissue with infrared thermography in the supraclavicular region, and also to find relations with the body mass index. As the research article performed by Jang et al. (2014), subjects were tested after a period o cold stimuli, but this one was established as the immersion of the left hand in cold water, during five minutes. It was verified that individuals with higher body mass index had lower SST and a lower variation between the SST before and after the cold stimuli. The referred authores considered that the increased concentration of subcutaneous fat, in children with increased body mass index, might have led to a thermal reaction, reducing SST. Thus, it is not possible to affirm whether the thermal action of brown adipose tissue was lower or if subcutaneous fat might have induced to a lower SST, but not a lower temperature of the tissue itself.

Subcutaneous fat has a different effect of brown adipose tissue, since it does not have a similar thermal action. It is known that white adipose tissue isolates temperature, interfering in the heat exchange between the skin and the environment (Henschel, 1967). Since it is concentrated in the most internal layer of the skin (the hypodermis), the most external layer (the epidermis), might have a reduced temperature. This phenomenon has already been described by Neves et al. (2015a). In men, using the skinfold method, the SST and the subcutaneous fat thickness, both of the subscapular region, were compared. It has been found a negative correlation between these two variables. In women, the same purpose was tested in the posterior region of the arm, but there has not been any significant result, in this case. Therefore, it is not possible to assume that the SST behaviour found in men could be generalized for any gender or body region.

Subcutaneous fat may not only alter absolute values of SST, but it may also interfere in SST variation during exercise, as showed in men. The effect of dynamic strength exercises in SST was tested with infrared thermography. During the exercises, SST inicially decreases, followed by a larger increase. In men with biceps skinfold thicker than 4mm, the variation of SST was lower, considering the difference between values from after and before exercise (Neves et al., 2015c).

Exceeding subcutaneous fat may lead to the development of gynoid lipodystrophy, also known as cellulite. This dysfunction was studied with infrared thermography by Nkengne, Papillon and Bertin (2013). These authors used a qualitative scale to classify the severity of the gynoid lipodystrophy and compared its results with the SST of the thighs. It has been found that in the highest levels of severity the SST decreases and the distribution of heat is less homogenous. Since the cellulite is a dysfunction that occurs in the subcutaneous fat, the cited study agrees with the assumption that fat mass would have a decreasing effect in SST.

Also referring to body fat in women, a research was conducted with females classified in either of two levels of body mass index, normal weight and obesity. The normal weight ones have not showed any relation between variables of fat and SST. The obese ones, however, have had significant negative correlations among SST of abdomen and thighs with body mass index, body fat percentage, visceral fat mass and subcutaneous fat mass, as assessed by means of bioelectrial impedance. Also, tympanic temperature has been compared between the groups of normal weight and obese women, with no statistical difference. The SST was significantly different between the two groups in the segments of arms, forearms, abdomen, lower back, thighs and shanks (Chudecka; Lubkowska; Kempińska-Podhorodecka, 2014).

A similar study was conducted with subjects of both genders, all of them professional athletes of several sports and with body mass index classified as normal weight. The SST of several body segments was compared between both genders. Statistical difference was found in nearly all regions of interest (ROI), excepting only the SST of the hands. Men have had lower SST values in the trunk than women. In all other ROI, women had lower SST values than men. The highest difference found was in the anterior shanks, which reached 0.81°C. In women, SST of the chest, abdomen and back had negative correlations with body mass index and body fat percentage, based on bioelectrical impedance. In men, only SST of chest and abdomen correlated with the body composition variables, while SST of the back correlated only with body fat percentage. The authors considered that the changes in SST might occur because of the insulating action of the adipose tissue, preventing part of the dissipation of endogenous heat from happening through skin (Chudecka and Lubkowska, 2015).

The same referred authors also conducted a study which investigated relations of the SST of several ROI in underweight women with anorexia nervosa, compared to a normal weight control group. Again, the technology used to assess body composition was bioelectrical impedance. In this case, the underweight women have had lower tympanic temperature than the normal weight ones. However, in the ROI of the back, abdomen, thighs and shanks, SST have shown the opposite effect observed in tympanic temperature. In agreement with the studied reviewed above, underweight women have had SST of the abdomen negatively corelated with body fat percentage, body mass index, subcutaneous fat mass and visceral fat mass. The SST values of the thighs have been also correlated with subcutaneous fat mass and visceral fat mass, and the SST of the lower back correlated with subcutaneous fat mass. Results agree with the assumption that heat dissipation through skin would be more intense in individuals with less body fat, which would increase SST in the ROI analyzed (Chudecka and Lubkowska, 2016).

It is important to highlight that in the research conducted with obese women (Chudecka; Lubkowska; Kempińska-Podhorodecka, 2014), as well as in the one with underweight women with anorexia nervosa (Chudecka and Lubkowska, 2016), the SST acquired in the hands have shown positive correlation with the variables of body fat, as opposed to the SST which have been found in ROI known to have more accumulation of adipose tissue, such as thighs and abdomen. The authors report that due to an intense vascularization in the extremities of hands and fingers, the difference of temperature between these body parts and the inside of the body might be balanced.

Savastano et al. (2009) have found similar information between SST of the abdomen and the body fat percentage assessed with a Dual-Energy X-Ray Absorptiometry (DXA) device, in both genders normal weight and obese adults. Other body segments were not observed, in this study, which does not allow us to compare these results with the ones from the researchers cited above. Also, authors have not parted the sample analysis between genders, which leads to a doubt about whether these results can be generalized for men or women.

Some of the studies analyzed here estimated models of linear regression between body fat percentage and SST, i.e., they investigated the possibility of assessing body composition with infrared thermography. The obese women analyzed by Chudecka, Lubkowska and Kempińska-Podhorodecka (2014), SST of the palms have had a value of R^2 of 36.6% and SST of the abdomen have had 77.9%, predicting body fat percentage. In the sample of normal weight and obese adults studied by Savastano et al. (2009), fingernail temperature have had R^2 equals to 45% and SST of the abdomen had 30%. On the other side, the study conducted with athletes have had less significant results, even though there have been satistical significance. In women, SST of the chest and of the upper back have had R^2 of 0.017% and 0.012%, respectively. In men, the same variables resultes in 0.006% and 1.06%, respectively, and, yet, of 1.04% based on SST of the upper back (Chudecka and Lubkowska, 2015).

In addition to the action of the adipose tissue in reducing SST, muscle tissue appears to have the opposite effect. This result has been shown by Neves et al. (2015d), who have found high SST associated with a high volume of muscle cross-sectional area in the biceps braquii, in men.

The DXA device, used by Savastano et al. (2009), is a device developed to assess bone mineral density. However, it is also useful to estimate body composition. Some authors consider DXA as the gold standard, in this sense, having considered it to have better accuracy than the bioelectrical impedance and the skinfold method. As it might be noticed in the prior analysis, there is very few information about the relation between SST with infrared thermography and body composition with DXA. For that reason, the authors of this chapter have developed a research with those devices, in the year of 2016. The study was part of the masters degree thesis of the main author of the present review of literature (Salamunes, 2017). The main contributions made by the author were published as a research article (Salamunes; Stadnik; Neves, 2017) and are described below.

In the study, a sample of 123 normal weight and overweight (non obese) women have been tested. Variables of SST of 30 ROI were compared with body composition values. The DXA device allowed the authors to estimate not only the total body fat percentage, but also lean mass and the fat percentage of five body segments: right and left upper limbs, trunk and right and left lower limbs. Pearson's correlations were calculated among temperature variables (minimum, mean and maximum SST of each ROI from abdomen, flanks, palms, posterior and anterior arms, forearms, upper limbs, thighs, shanks and lower limbs) and total body fat percentage. Most of the correlation results have been negative and significant, especially referring to mean temperatures. Palm mean temperatures have been positively correlated with body fat percentage, in agreement with the studies cited above. Only the mean SST of the flanks has not showed significant correlation.

In our study (Salamunes; Stadnik; Neves, 2017), a secondary analysis was conducted. Values of fat percentage of each of the five segments were assesses and used to divided the sample in groups. Therefore, five independent subdivisions were made in order to classify women with high and low fat percentage on each segment. Between high and low fat percentage groups, mean SST were compared with Student's t test. For groups classified using upper limb fat percentage, ROI of arm, forearm and upper limb were compared. For groups classified using trunk fat percentage, ROI of the abdomen and flanks were compared. For groups classified using lower limb fat percentage, ROI of thigh, shank and lower limb were compared. Since it is known that muscle mass may also interfere in body fat percentage and SSt results, lean mass from each limb was also compared with Student's t test.

Only the left upper limb have had significant difference in lean mass, between groups. All other segments have not showed any difference. Therefore, it has been considered that results of these variables have not been affected by the muscle mass. The SST value has been higher in the groups with lower fat percentage in the referring segment. Right and left palms, right and left posterior forearms, flanks and anterior right leg were the only ROI of which the SST did not differ between high and low fat percentage groups. In our study, we concluded that the high fat percentage of the segment tends to decrease SST, as expected.

Finally, still in our study (Salamunes; Stadnik; Neves, 2017), three mathematical models were developed using infrared thermography and body circumferences, aiming to estimate total body fat percentage. In this analysis, SST values were considered as the average value between right and left ROI, in the bilateral limbs. The most significant model of linear regression was obtained with the variables of mean SST of posterior lower limbs, minimum SST of posterior arm, maximum SST of palms and abdomen circumference, reaching a R value of 0.764 and R^2 equals to 58.3%. The second model was similar, but abdomen circumference was replaced by hip circumference, with values of R equals to 0.750 and R^2 equals to 56.2%. The last one was developed with the same variables as the first one, but without maximum SST of palms. The results were R of 0.738 and R^2 equals to 54.5%.

Based on the analysis conducted in this chapter, it is possible to affirm that body composition – subcutaneous adipose tissue, visceral fat mass, body fat percentage and muscle mass – interfere in SST, as measured by means of infrared thermography. However, literature still lacks studies in this bias with DXA. As it has been showed above, there is a tendency of significant linear regression to estimate body fat percentage with SST, negatively correlated, in most cases. These results have been more significant in obese populations, which clarifies the need to improve the data already published in literature about normal weight and overweight non obese individuals. It might also indicate that SST does not suffer major alterations in populations which are not considered to be obese with body mass index.

CONCLUSION

It can be concluded that body composition interferes in SST. In most body segments, body fat percentage and subcutaneous fat tends to decrease

SST, while in hands (both palms and posterior hands) the effect is the opposite. This result is probably due to the difficulty of releasing heat through skin in body parts which have exceeding adipose tissue. As showed above, the use of infrared thermography to estimate body fat percentage appears to be possible and useful, when environmental control is properly taken care of. It was not possible to conclude whether body fat interfered in the studies about medical diagnostics and sports sciences, since this variable was not controlled by the cited authors. Therefore, the authors of the present study believe that it is important that researches using infrared thermography, in several applications, consider the influence of the adipose tissue in its interpretations, since body fat may alter temperature results.

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Chapter 4

CHALLENGES OF THERMOGRAPHIC IMAGE IN MEDICAL APPLICATIONS

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ABSTRACT

The ability to detect pathological changes early and in a non-invasive way represents important advantages in the medical field. Diagnosis should become less intrusive, more accurate and less expensive in order to implement in the clinical routine. Infrared thermography has the advantages of being non-invasive, fast, reliable, capable of producing multiple recordings in short intervals, and absolutely safe for patients and clinicians. Thermographic image (TI) came to be an extensively studied

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technique to quantify sensitive changes in skin temperature in relation to certain diseases: early in the pathological process (lesions, inflammation and infection) the circulation fluxes are altered and, consequently, the tissues’ temperature is reflected in thermography pattern, before structural or functional changes can be observed. This technique proved to be able to give relevant clinical information, such as breast cancer, foot disease in diabetes, rheumatoid arthritis and sports injuries. Monitoring the temperature profile of a patient will allow understanding the physiological evolution of some diseases or monitoring the pharmacologic therapy effect. However, the high cost of this technology and the small number of commercial solutions do not allow a general implementation in the clinical environmental. The future direction is the combination of this technique with the other images techniques in order to add clinical information for a more reliable diagnostic.

Keywords: medical thermography; thermal imaging; skin temperature; biomedical solutions; non-invasive instrumentation

1. PRINCIPLES OF THE TECHNIQUE

Infrared radiation (IR) is energy radiated by the motion of atoms and molecules on the surface an object with a temperature more than absolute zero (–273, 15°C = 0 Kelvin). The intensity of the radiation emitted is a function of the temperature of the material, it means that a higher temperature, correspond a greater intensity of infrared energy that is emitted [1, 2]. The materials emitted infrared energy and also reflect infrared, absorb and in some cases, transmit [3]. The wavelength of the infrared radiation band extends from near infrared (0.78 μm) to far infrared (1000 μm), limited in the electromagnetic spectrum by the visible light (lower wavelength than 780 μm) and by the microwaves (wavelengths higher than 10^3 μm) [4].

The measure of the ability to radiate thermal energy is called emissivity. A perfect black body has an emissivity of one, which means that at any given temperature difference with the environment, it radiates the maximum possible energy. The energy radiated by the black body is defined by the Planck’s law, and the Stefan Boltzmann law describes the spectral radiant emittance of a particular wavelength [5, 6]. When the temperature of the material equals its surroundings environment, the amount of thermal radiation absorbed by the object is equals to the amount emitted by the object [3]. The emissivity of a body is defined as the ratio between the radiant energy emitted by any object and the radiation, which would be emitted by the black body at the same temperature. At steady temperature, the energy absorbed by the perfect black body will be equal to the energy emitted; whereas, in practice, this ideal behaviour could not be observed and the transmissivity and reflectivity may also be involved [4, 5]. In clinical practice, the dry human skin which has an emissivity of 0.98, is considered to be a perfect ideal black body with a maximum emission wavelength at about 9.3µm.

Measurements of the intensity of the radiation emitted from the surfaces of bodies at any particular wavelength represent one method for the measurement of surface temperature without contact. IR represents one of these electromagnetic radiations, where the intensity of the infrared radiation emitted by objects represents a function of their temperature. Infrared thermography is a technology that commonly uses an infrared thermal camera to capture the temperature distribution of a surface being examined and display it as a visible information as a thermal image [2].

Infrared scanning devices are used to convert infrared radiation emitted from the human skin surface into electrical impulses that are visualised in colour on a monitor [2]. This visual image graphically maps the body temperature and it is referred to as a thermogram. A temperature value is allocated to each pixel and they are then displayed as a specific colour, which is determined by the selected colour palette. The spectrum of colours indicates an increase or decrease in the amount of infrared radiation being emitted from the body surface. The colours are properties of visible light that do not exist in the infrared world. In order to allow the visual analysis a maps of colours is created with the conversion of these images into visible light, the thermogram assigns dark colours to the coolest temperatures in an image, clear to the hottest temperatures in an image, and graduating shades in between [2].

For this technique is essential the standardization of procedures for clinical protocols including patient preparation, body positions for image recording and evaluation of thermal imaging [7–9]. The use of external reference temperature sources is an important recommendation for regular calibration checks. Different areas of human body were used for the thermogram analysis [10, 11]. The definition of these regions of interest remains a great challenge to accurately determine the boundary of a region of interest in a consistent and unambiguous manner. Other factors due to patient's preparation and temperature control of the examination room may also contribute to poor reliability of thermal images. The room should be of adequate size (enough space for the equipment and freedom for the patient movement and position) and maintain a homogenous temperature and the constant humidity. The temperature of the room should be such that the patient's physiology is not influenced [12].

Thermography is a non-contact, non-invasive method which is able to scan and visualize the temperature distribution of entire surfaces quickly and accurately and is widely applicable in a variety of different fields in industry and research [13]. The high prices and the weak performance of the infrared thermal camera delayed the wide use in the clinical environment. However; over two decades ago, TI has increased in popularity and became an increasingly common investigation technique with the greater availability and falling prices of infrared thermal cameras [13, 14].

2. SKIN TEMPERATURE CHARACTERIZATION

The temperature of the skin itself plays a role in maintaining the core temperature. Skin temperature is a function of the heat that reaches it from the core (and its metabolic process) and the external temperature [38]. Energy taken into the human body has different ways of distribution (chemical, mechanical, electrical, thermal, etc.). The organism's heat loss depends on external factors and is the result of conduction (3%), convection (12%), IR radiation (60%), and of evaporation (25%) from the surface of the skin, while heat is lost via breathing as well [38, 14]. The infrared radiation is responsible for the majority of heat is lost from the skin. The IR emissivity of human skin is high and measurements of infrared radiation emitted by the skin can be converted directly into accurate temperature value [39].

The sympathetic nervous system is the most important component in controlling the body temperature because it regulates the circulation and thus the conduction of the heat to the skin. The main function of the skin blood flow is maintaining of the constant body temperature, even when the ambient temperature is different. The blood flow to the skin is about 5% of the cardiac output under normothermic conditions but it may vary from nearly zero during periods of maximal vasoconstriction to as much as 60% in times of maximal vasodilation when the body temperature is elevated. Skin blood flow changes dynamically due to the continuous interplay between the vasoconstricting and vasodilating mechanisms influencing skin blood flow [42], and reflect phenomena associated with changes in autonomic nervous system [42].

With the increasing relevance of TI technique, studies about the correlation of temperature with individual characteristics - such as age, gender, BMI, fitness - start to emerge as the characterization of regions in the human body. The skin temperature showed an inverse correlation with body mass [10, [15–17]. Human obesity is associated with increased heat production; however, subcutaneous adipose tissue provides an insulating layer that impedes heat loss, which explains the inverse correlation obtained in the studies, between skin temperature and the body mass [10].

The age induces skin structure changes, such as decrease vascularization, chronic diseases processes, and diminished ability of aged skin to a reduction of cutaneous blood flow (vasoconstrict) [18]. Some differences between skin temperature were found between different ages [19, 20], but it is a field not very well studied.

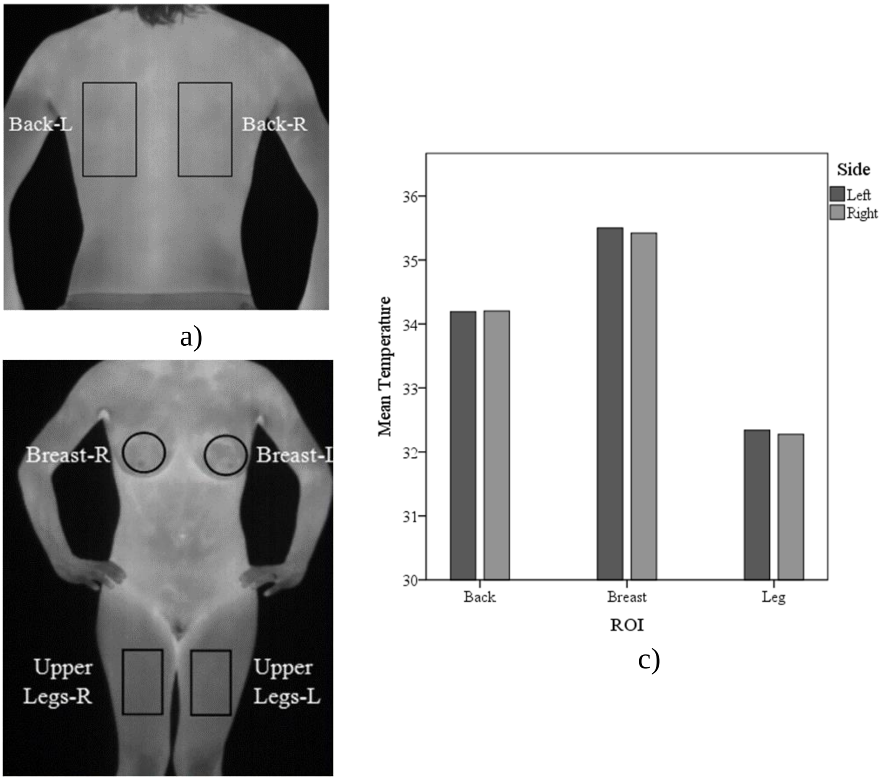
Due to the difference in the body fat distribution expected between males and females, there are differences in the average skin temperature and also significant gender related differences in the skin temperatures of specific regions [21, 22]. However, the other studies did not find a significant difference on an average skin temperature between the two genders [23].

Physical condition also influences the skin temperature, due to the effect of trained people usually having greater capacity for heat transfers between the core and the skin in consequence of the higher blood flow and lower body fat [24]. Furthermore, the skin temperature changes during the exercise activity could be monitored by thermography techniques [25], showing that temperatures values for the skin are higher over muscles than over other structures and the distribution differed dramatically from that observed before exercise [26].

Smoking affects peripheral circulation and as consequence is expected a lower skin temperature in smokers. The nicotine has a vasoconstrictive effect causing a reduction in the amount of blood flowing to certain parts of the body, e.g., the extremities and therefore it may reduce skin temperature [24, [27–29]. The impact of the smoke effect in the skin and the peripheral circulation could be evaluated with thermography.

The monthly menstrual cycle in women is accompanied by rhythmic changes in core temperature. Menstrual cycle induce variations in distal and proximal skin temperatures. Was verified an increase in the skin temperatures during the luteal phase than in follicular phase [24, 30]. The oral contraception also induces changes in the woman thermal skin. Women on oral contraceptives had more frequent intense vascular patterns [31]. Increase progesterone is associated with increased skin temperature as well the threshold temperatures for active cutaneous vasodilation. The oral contraceptive use shifts baseline core temperature and the threshold for the active vasodilator system to higher internal temperatures. This shift in active vasodilation results in a lower skin blood flow [32].

The correlation between skin temperature and individual characteristics remains understudied. Extensive population studies are missing, which allows to identify of the individual characteristics influence with skin temperature profile [9]. A deeper characterization this influence patterns of skin temperature could open new perspectives and interesting applications for the thermographic techniques, knowing that skin temperature gives information about thermoregulation and the autonomic nervous system function. Considering this, the evaluation of drugs effect or stress conditions response could have interesting results with skin temperature.



a)

b)

c)

Figure 1. Mean temperature for upper back region, breast and upper legs and the differences between left and right side [data from [17]]. a) Region for the measurement temperature in the back; b) Region for the breast and upper leg for temperature measurement; c) Temperature results for the three regions and the differences between the left and right sides.

The skin temperature is not the same in any region, as there is a profile of temperatures for the human body. In both women and men, the highest temperatures were found on the trunk and face [17, 33]. In the female case, the breast showed the higher temperatures [17]. The temperature of the skin is lower over protruding and markedly curved parts, such as the nose, ears, fingers and toes, and is higher over muscles than over bone or tendons, and in an active organ than over one in the rest [34]. Generally, the temperature of the skin in the extremities is lower than the head and the torso. The extremities also show greater fluctuation when the body is exposed to changing environmental temperatures [34].

During pregnancy the female body undergoes significant changes in size and vascularity and the uterine volume increase leads to a higher number and size of blood vessels [35]. Recently, the profile of the temperature of a pregnant woman was studied, where 31 regions all over the body were measured [17]. The results confirmed the higher temperatures for the breast region (Figure 1) and the symmetrical skin temperature for the healt subjects was also verified (Figure 1c). In a sample with 61 healthy pregnant women, the skin temperature showed a symmetrical distribution, with the symmetrical areas differing less than 0.5ºC, with a mean of 0.25 ± 0.23ºC [17]. Also, after the pregnacy phase, women who had lactated for more than 10 months also showed increased intense vascular patterns in the breast [36].

3. APPLICATIONS IN BIOMEDICINE

The skin temperature of the human body is an important physiological parameter and an accessible and useful measurement for investigating some aspects of peripheral circulation, thermoregulation and structural changes in several diseases that cause localized increases in temperature, which show as hot spots or as asymmetrical patterns in skin temperature. Thermography has several important features for medical measurements, such as non-invasive, non-contact, reliable, capable of producing multiple recordings at short intervals, and safe for patients and clinicians. Moreover, advances in infrared detectors (better temperature sensitivity and spatial resolution) boosted the use of this technology in medical applications and is becoming an accurate medical diagnostic tool for abnormal temperature pattern measurements. Infrared thermography has been successfully used in diagnosis of several diseases and proved as a useful tool to access important information that may help in disease diagnosis and monitoring the therapeutic effect and the evolution of pathologic conditions.

The knowledge of physiological mechanisms of temperature distribution on the body surface are now better understood. This has resulted in more evidence for the value of thermal image in the diagnosis of a disease [8]. Infrared thermography is used to measure and analyse physiological functions and pathology related to the body’s thermal homeostasis and temperature. The correlation between body temperature and diseases has been known for centuries, but in recent years, due to rapid development of new technologies, skin temperature has been used as a convenient and effective diagnostic tool to detect diseases [5, 13]. In clinical medicine thermography was initially used to search for breast cancer. In 1956 thermometer started to be used for measuring temperature difference on breast’s skin surface covering the malignant tissue [37]. In 1972, the thermography was considered as a preliminary screening test for the breast cancer in USA [38]. In 1987, the importance of medical thermology as diagnostic imaging modality for the assessment of local skin temperature was recognized and accepted as an indicator of pathology [39].

Elevated skin temperature, or fever, is often associated with a host of systemic illnesses, such as acute viral and/or bacterial infections. It is also associated with increased local circulation from inflammatory processes. One of the main symptoms of acute inflammation is heat. Increase in the body temperature during inflammation can happen locally as well as systemically [40]. The clinical signs of inflammation and soft tissue injury are often too subtle to be detected by the individual or even trained health care professionals. The five signs of inflammation include: pain, erythema, oedema, loss of function and heat. It is difficult to assess these subtle parameters, with the exception of skin temperature [41]. The visualization of temperature distribution on the surface of the human body can provide valuable diagnostic information, and is mostly a reflection of the processes inside the body.

An important focus has been done into the medical application, covering a large range of pathologies and analysis of the potential of thermography for the diagnosis and monitoring. The infrared thermography has been applied to study a number of diseases where skin temperature can reflect the presence of inflammation, infection, or others that change the blood flow or the symmetry due to a clinical abnormality [8, 43]. The temperature contrast in the affected regions is about 0.7 to 1ºC above the normal regions, due to sluggish blood circulation [44].

Due to the incidence of breast cancer and the extreme requirement to have techniques that allow the early detection, the thermography was applied to this disease [37, 38, 45–48]. Tumors generally have an increased blood supply and an increased metabolic rate which leads to localized high temperature spots over such areas [43, 47]. The surface temperature for a malignant breast showed higher values than that of a normal one, and the size and location of the tumour do have an effect on the surface temperature distribution [46]. Figure 2 show the thermography image of the vessels in breast region for two health women. This figure represent a symmetrical breast where is clearly visible the vessels in this area.

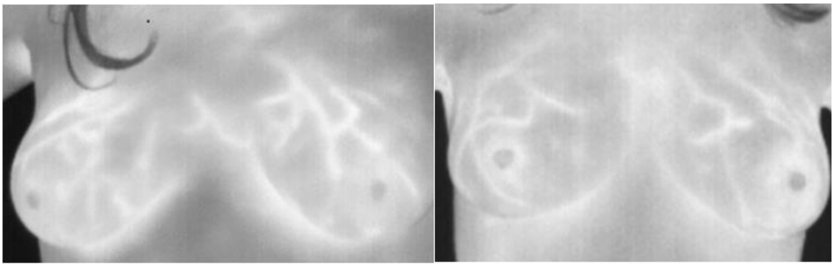


Figure 2. Thermographyc image of the breast. Is clear identify the vessels in this region that is one of the most irrigated and with higher temperature [17].

Associated with breast cancer, there are also the cases of patients that are underwent reconstruction following mastectomy. In microvascular free flap surgery, monitoring plays a critical role in detecting early postoperative vessel thrombosis. Flap temperature monitoring revealed a trend in temperature that correlates with anastomotic thrombosis and eventual flap failure [49]. Flap skin temperature assessment can be used as a monitoring method in plastic reconstructive surgery to improve patients' safety [50].

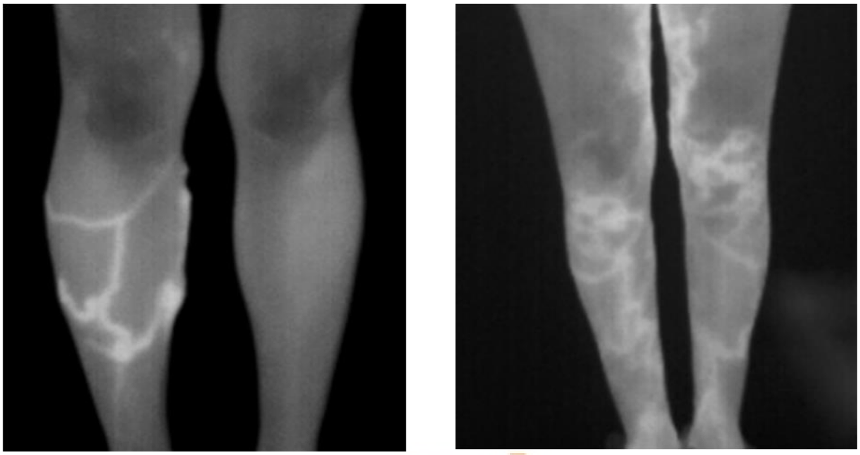
The efficacy of therapeutic drugs that can change the blood flow through the skin vessels and alter the heat radiation of the skin surface can be studied and monitored using thermography [14, 55], 56]. For some diseases as the breast cancer is important to have a technique that enables the evaluation of drug efficacy, particularly in the first few hours after administration but avoiding the expensive images techniques such as MRI [56]. The thermographic image also could evaluate the effect of a cream applied in the skin. The decrease of skin temperature associated induced by the use of dermocorticoid cream was monitored using the TI [57].

In the Raynauds phenomenon, thermography provides useful information to quantify the damage, the time evolution of the disease, and to assess recovery after the treatment [8, 43]. In rheumatoid arthritis, thermography was used to identified the abnormal temperature distributions over joints and to evaluate the therapeutic efficacy of different treatment approaches [43, 44, 51].

Infrared thermography was used to measure body temperature in neonates during their first month of life for the identification of intestinal necrosis [52]. The particular features of neonatal patients the non-contact techniques are essential. This initial study suggests more studies and other applications for the thermographyc image information of neonatal physiology [52].

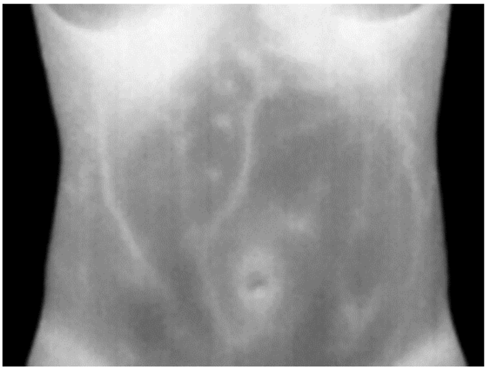
Thermal research of skin temperature on human athletes allows screening individuals for sports injuries and also concluded that exercise induced physiological functions that can be identified by thermography [53]. Since muscle injuries trigger inflammatory processes and inflammation generates heat due to increased local metabolism, consequently the level of inflammation can be measured by the temperature gradient [54]. The thermogram also was used to determine the overuse reactions, called minor traumas that are very frequent and the early detection is critical to avoid injuries [53]. These regions are usually identified by the asymmetries in the members. Thermography is a remote sensing technique, and this feature allows monitoring the body surface temperature during and after the exercise, and detecting the changes in skin temperature caused by the exercise [25, 53]. The study of the skin temperature during the exercise shows an interesting profile [25]. At the beginning of exercise, the increased oxygen supply to muscles implies a larger demand of blood flow to active muscles and thus a reduction of cutaneous blood flow (skin vasoconstriction) an consequently the temperature decrease during the initial stage. During the exercise heat starts to accumulate into the body due the intense metabolic heat production, and blood redirected from the body core to the surface (blood perfusion) as a result the skin temperature tends to increase [25].

The human body usually exhibits a high degree of symmetrical temperature distribution. Thermal symmetry of the human body has been defined and the maximum value accepted is 0.5 - 0.3ºC for two bilateral regions to be considered symmetrical on healthy people [58]. The studies with health pregnant subjects confirm the higher symmetry for an extensive characterization of the human body [17]. Since there is a high degree of thermal symmetry in the normal body, subtle abnormal temperature asymmetry’s can be identified, signalizing abnormal physiological processes (Figure 3).



a) b)

Figure 3. (Continued)



c)

Figure 3. Thermographic image with visible asymmetry in three subjects [data from [17]]. a) Asymmetric structure of vessels in the right leg; b) global asymmetric vascularization in the legs; c) some asymmetric vessel identified in a belly of pregnant woman.

The asymmetry in the temperature between corresponding sites of the left and right foot is an early warning sign of foot disease in diabetes [59, 60]. The diabetes and the peripheral sensory neuropathy associated was studied using the infrared thermometry to monitor wound inflammation, and higher temperatures on the ulcerated foot than those on the contralateral foot were verified on initial presentation [61]. Diabetic foot ulcers are preventable through the early detection and timely treatment of signs of diabetic foot disease. Thermal imaging is a promising technology to achieve this objective, as increased plantar foot temperature is a key signal of inflammation process [62].

The development of automatic solutions based in thermographic image technique avoids the subjective effect induced by the operator during the evaluation and allow it use by the subjects and patients in their life's [62], monitoring the risk cases and decrease the time for the abnormal physiological detection that will improve the changes for the therapeutic response.

The most recent developments combine thermography image with other images techniques [63]. Multimodal medical image fusion combines information of one or more images in order to improve the diagnostic value. The combination of these techniques permits the simultaneous visible surface and subsurface inspections [64].

CONCLUSIONS AND CHALLENGES FOR THE FUTURE

Infrared thermography has been shown to be an important and accurate tool in the detection of several pathological phenomena, often before any visible signs of damage exist; and monitoring the drugs effect or a natural physiological process as a pregnancy.

The early detection of some pathologic processes allows a higher probability of the therapeutic success. Non-invasive techniques are the most interesting and important solutions for screening the abnormal changes in the human body. Driven by this, thermography solutions are extending the area of use in the medical field. The technology advances also allow more applications, with more cheap and accurate cameras.

For some specific pathologies such as diabetic foot ulcers, the frequent monitoring is essential, and a future thermographic images solutions can have impact to reduce this abnormal process or increase the chances for the therapeutic response. This approach requires cheap cameras in order to reduce the cost of the equipment and automatic methods for the first clinical evaluation.

Another interesting challenge for TI is the combination of thermography image with other image techniques that will allow exploring a huge number of applications and ensuring a better and robust image diagnosis. On the other hand, the development of the technology will decrease the price of the equipment and will allow their use in more clinical studies, increasing the fields of application in the biomedicine. However, the combination of image techniques requires a higher computational development and expensive systems.

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